

Heat Removal System for Fission Converter Tank

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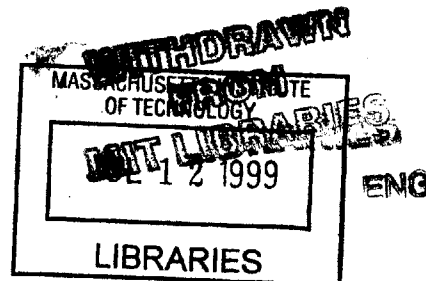
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ABSTRACT

A new fission converter based epithermal neutron medical facility at the Massachusetts Institute of Technology Reactor (MITR) uses 11 fuel elements which are placed into the fission converter tank and which produce a maximum of 250 kW of heat. The heat removal system for this fission converter tank has been designed and is described. This design must operate with both light water and heavy water as the coolant.

This heat removal system is divided into four subsystems : the primary system, the secondary system, the clean up system, and the cover gas system. For the primary system, the thermal hydraulic analysis shows that the flow rate in the system is 110 GPM at a ΔP of 19.5 psi with two pumps operational. If only one pump is operational, the flow rate is 84 GPM at a ΔP of 13 psi. Both flows are greater than the flow rate needed to assure that the temperature of the coolant will not reach the critical temperature for onset of nucleate boiling. For the secondary system, the necessary flow rate is calculated to be 76 GPM at a head loss of 15 ft of water.

The clean up system is designed to have a flow rate of 0.8 GPM at a ΔP of 9.7 psi. For the purpose of decay heat removal, a diaphragm valve will be used to control this flow rate.

The analysis of the cover gas system showed that a feed and bleed system would be acceptable.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Cancer is one of the most dangerous diseases and cause death. Although early detection and modern modalities of treatment have increased the possibility of cure significantly over the past years, there are still several types which still cannot be treated effectively¹.

Boron neutron capture therapy (BNCT) is a binary cancer therapy modality that may be effective in the treatment of cancers which cannot be cured by conventional modalities. BNCT consists of two components: a drug containing non-radioactive ^{10}B and a neutron beam^{2,3}. A boron-containing drug is selectively taken up by the tumor tissue. Then a fission reaction occurs when a neutron is absorbed by ^{10}B and emits an α particle and a ^7Li ion. These heavy charged particles carry 2.310 MeV of kinetic energy (in the excited state) or 2.792 MeV (in the ground state). Their energies then are deposited within 12 – 14 microns, which is the range of the size of most cells. Therefore, the damage is restricted to the tumor cell in which the boron was located, leaving nearby healthy tissues intact^{1,4,5}.

In order to expose the tumor to thermal neutrons, the use of epithermal neutron beams has been implemented. These beams have a range of energies between 1eV and 10 keV which are sufficient to penetrate the skull and reach the tumor.

1.2 FISSION CONVERTER PROJECT

BNCT trials are currently being conducted at MIT using the medical facility shown in Figure 1-1. The current beam has an epithermal neutron flux of 2×10^8 n/cm²sec^{6,7}. With this flux level, the average length of irradiation is three hours which is difficult for the patient and will become a hindrance for routine therapy once advanced clinical trials begin.

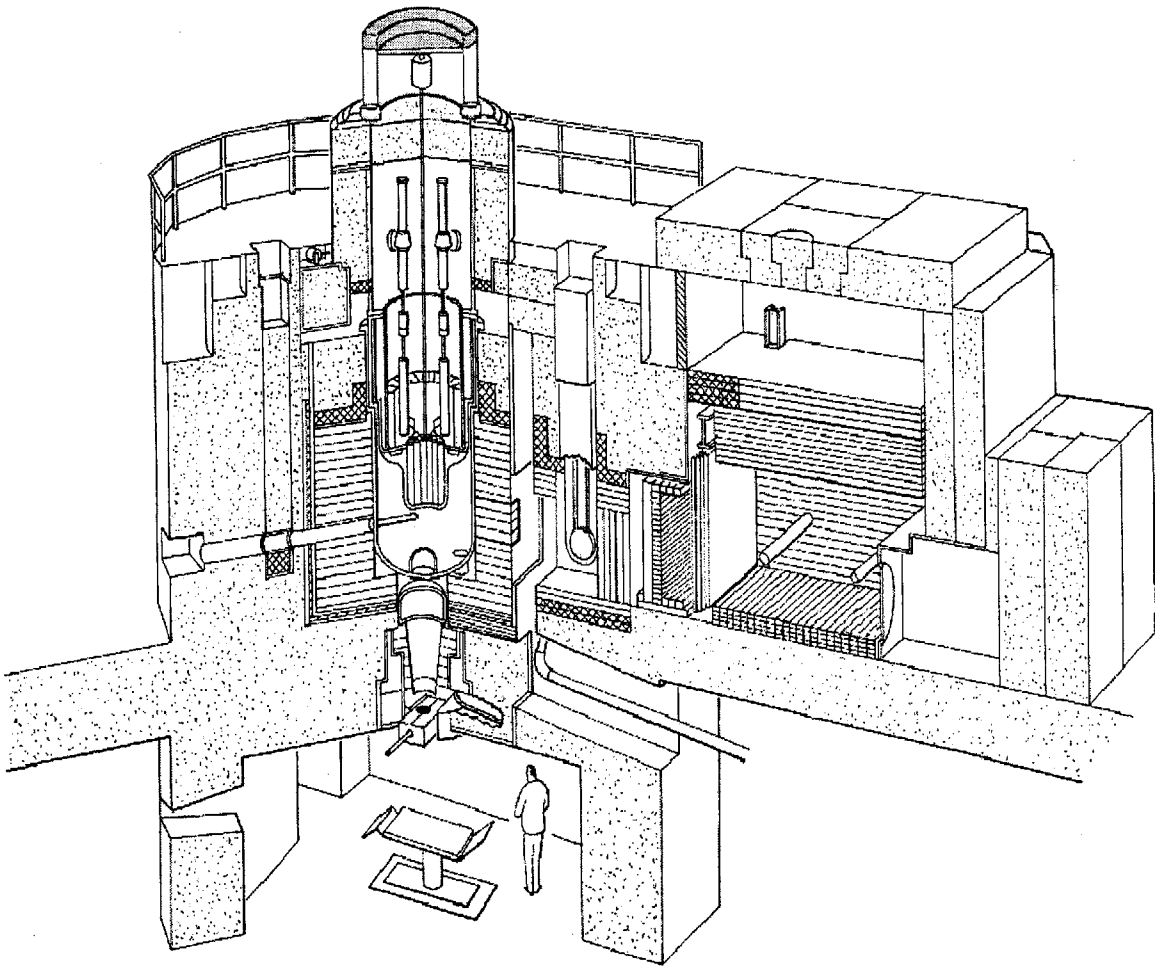


Figure 1-1. Isometric view of current medical facility at MITR.

By delivering a better quality and higher in intensity beam of epithermal neutrons, the irradiation time can be shortened and the therapeutic ratio can be increased⁸. In order to get a better quality beam, the use of a fission converter plate source has been proposed^{8,9,10}, and such a facility is under construction at MIT. This plate of fuel elements will cause a fission reaction when hit by neutrons from the reactor core^{8,9,10}. These fission neutrons are then moderated down to the desired lower energy epithermal neutrons, while fast neutrons and gammas are filtered out of the beam. Thus the result is a high quality epithermal neutron beam with a flux two orders of magnitude higher than the current facility^{8,9,10}. Therefore, time of irradiation will be reduced to a few minutes instead of hours. The proposed facility is shown in Figure 1-2.

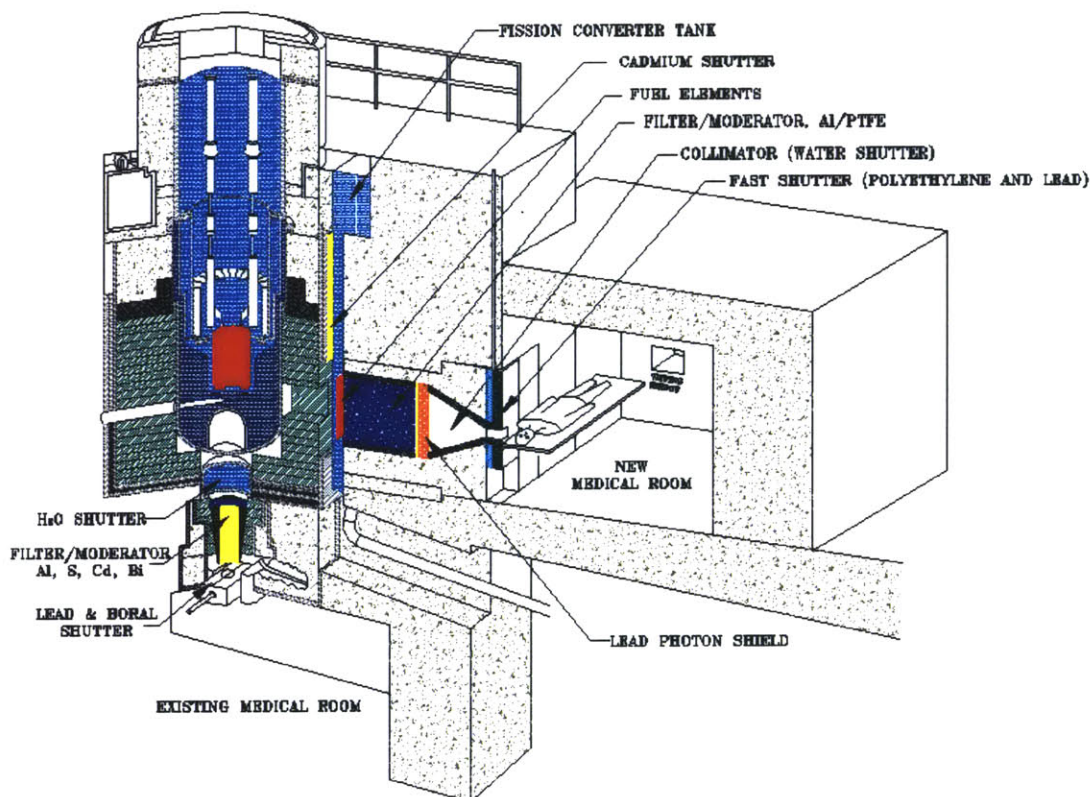


Figure 1-2. Isometric view of proposed design for new medical facility at MIT.

1.3 OBJECTIVE

The fuel elements in the fission converter generate substantial power. The heat generated has to be transported out of the system to prevent excess temperature in the aluminum fuel elements. Specifically, the temperature should be prevented from reaching the softening temperature of the aluminum fuel ($\sim 450^{\circ}\text{C}$)¹⁰. When the MITR power is at 5 MW, the heat generated is projected at 103 kW, if the reactor is upgraded to 10 MW, the heat of 206 kW will be produced. The analysis here will be based on 250 kW. The previous analysis and design done by B. Sutharshan¹⁰ concluded that to provide a safety margin, forced convection was the best means of heat transfer. His analysis showed that the necessary flow rate through the fuel elements was 4.6 kg/s with a temperature difference across the hottest fuel element of 20°C and an exit coolant temperature from the hottest fuel element of 60°C .

The objective of this work is to implement, modify and manufacture the heat removal system designed by B. Sutharshan¹⁰ for the fission converter using either light water or heavy water as the coolant. The system itself consists of four subsystems: primary, secondary, clean up, and cover gas. The objective includes the following sub tasks :

1. Implementing the forced convection heat removal system designed by B. Sutharshan¹⁰.
2. Identification of necessary components.
3. Preliminary layout design of the heat removal system.
4. Analysis of all four subsystems.

5. Obtaining specifications for the necessary components.
6. Ordering the necessary components.
7. Testing the components.
8. Final layout design of the heat removal system.
9. Manufacturing the heat removal system.
10. Implementing and testing the heat removal system.

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CHAPTER 2

PRIMARY AND CLEAN UP SYSTEM

2.1 INTRODUCTION

2.1.1 Primary System

The primary system is the main system of this heat removal system. Its main purpose is to reject the heat produced in the fuel elements to the reactor secondary coolant. The flow rate of the primary system is designed to be 4.6 kg/s or about 67 GPM¹. The primary system consists of 2 primary pumps, a shell and tube heat exchanger, instrumentation, storage tank, piping and fittings. All of these components are made out of stainless steel due to the use of heavy water (D₂O) in this system. Furthermore, all of these components will be mounted on a steel skid so that the system can be moved if necessary.

The reasoning behind having two primary pumps working in parallel is that if, during a patient irradiation, one of the pumps failed, the irradiation could still be finished¹. The instrumentation consists of a venturi flow meter, temperature gauges and pressure gauges. As for the piping and fittings, it has been decided that 2 in. nominal diameter pipes should be used.

The primary system is interconnected with the clean up system¹ as shown in the schematic diagram of both systems in Figure 2-1. The design layout for the primary

system is shown in Figures 2-2 and 2-3 while the flow direction layout is shown in Figure 2-4.

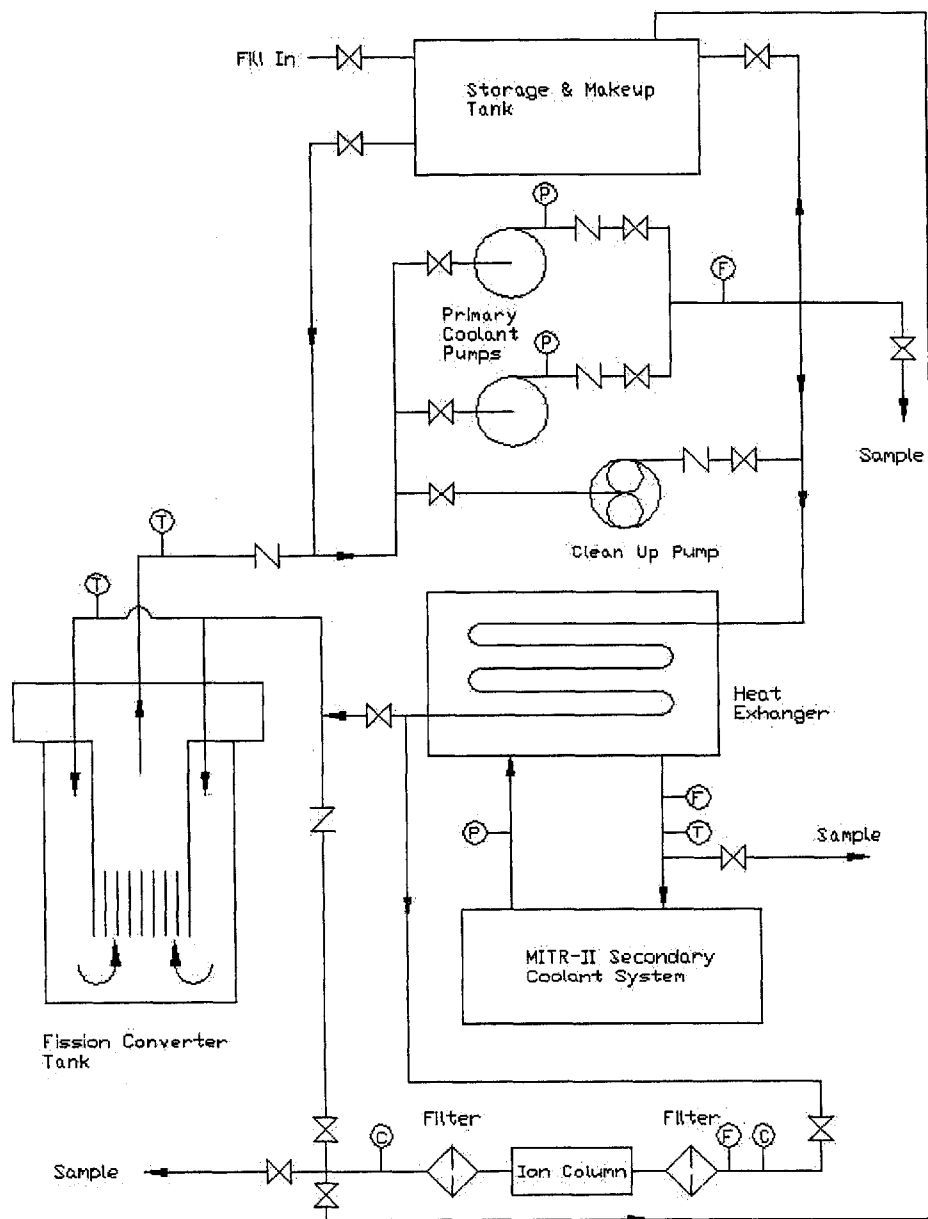


Figure 2-1. Schematic diagram of primary system and clean up system.

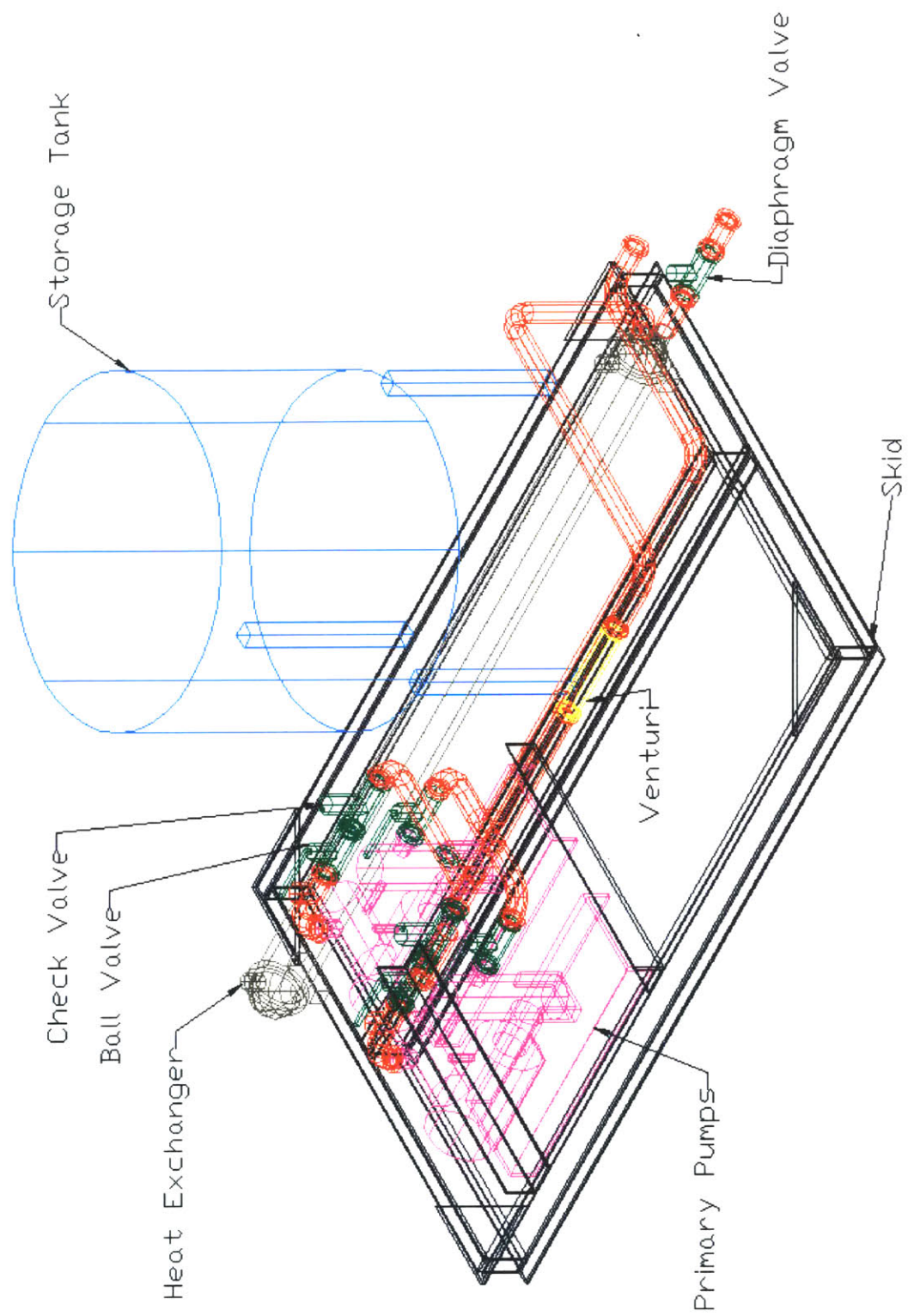


Figure 2-2. Layout design of the primary system.



Figure 2-3. Solid diagram of primary system.

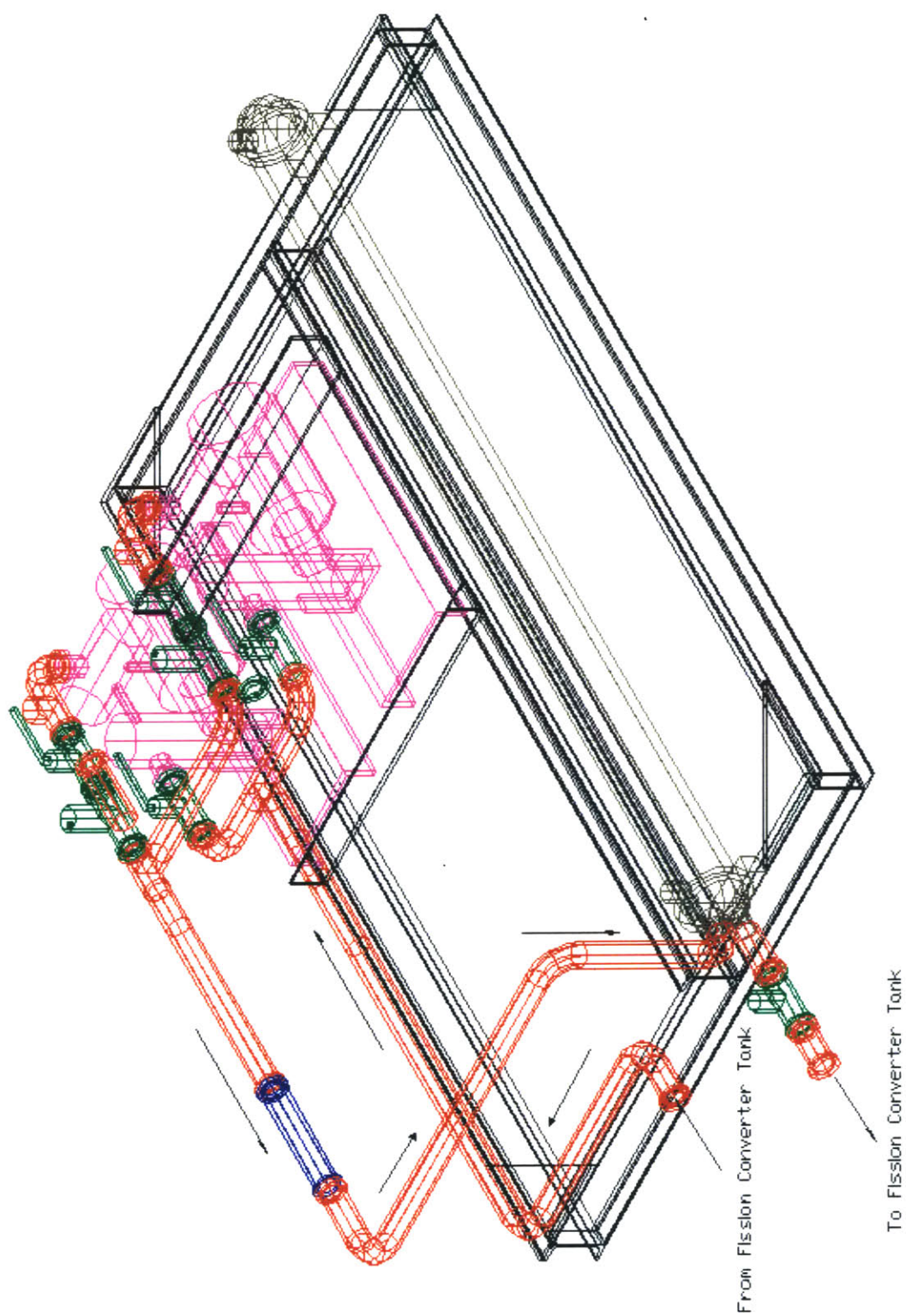


Figure 2-4. Flow diagram of the primary system.

2.1.2 Clean Up System

The clean up system is a small system consisting of tubing, piping, fittings, an ion column inlet filter, two ion exchangers, an ion column outlet filter, instrumentation, and the clean up pump². The tubing, piping and fittings, ion column outlet filter, and the clean up pump are made of stainless steel. For the ion column inlet filter, and the ion exchangers, the material is plastic. The filters and ion exchangers with the instrumentation are mounted as shown in Figures 2-5 and 2-6.

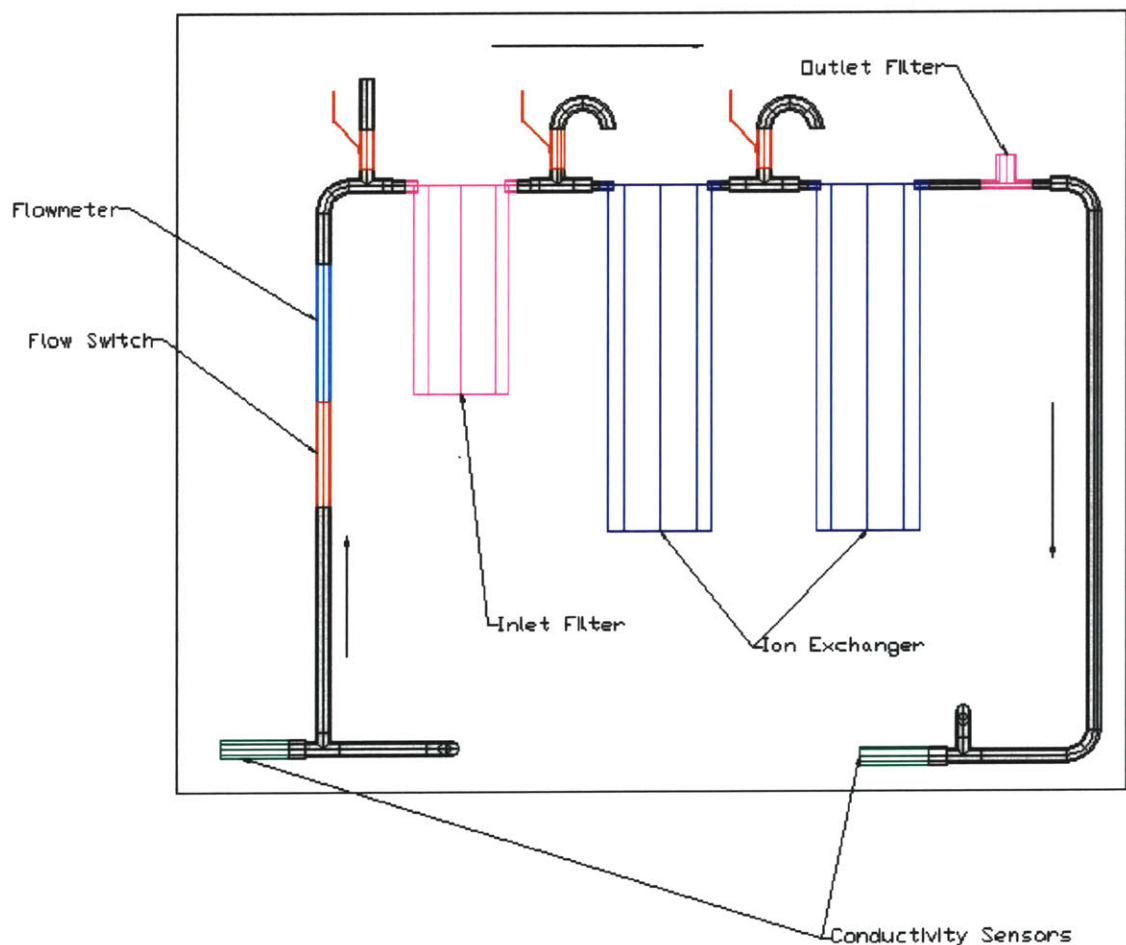


Figure 2-5. The layout of the clean up system component on the board.

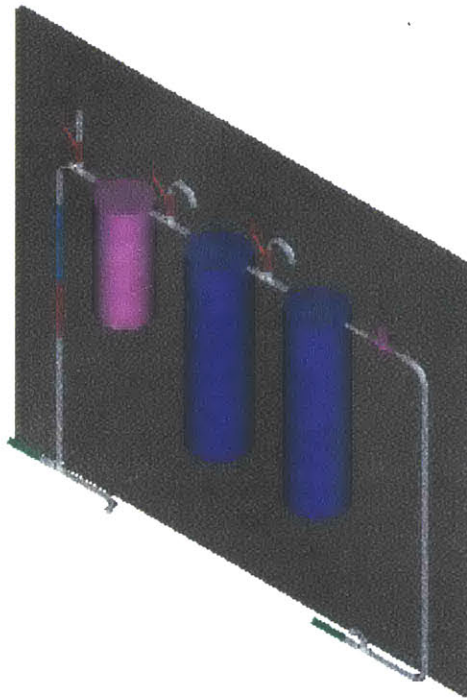


Figure 2-6. Solid diagram of mounted clean up system components.

Half inch diameter tubing and piping are used in this system. The instrumentation consists of 2 conductivity cells; one will be placed at the inlet of the clean up system, the other will be placed at the outlet of the clean up system, and a flow meter.

The purposes of this system are to monitor the conductivity of the primary coolant and also to remove any impurities from the heat removal system. Some other uses of this system are for removing decay heat from the fission converter².

The location of the clean up system is downstream from the heat exchanger in order to maintain a low coolant temperature so as to protect the temperature-sensitive ion exchanger resin². Only about 5% of the total flow of the primary system will go to the cleanup system and it will then be returned to the main system flow². The design layout of the clean up system is shown in Figures 2-7 and 2-8 while the flow direction layout is

shown in Figure 2-9. The design layout of the clean up system together with the primary system is shown in Figure 2-10.

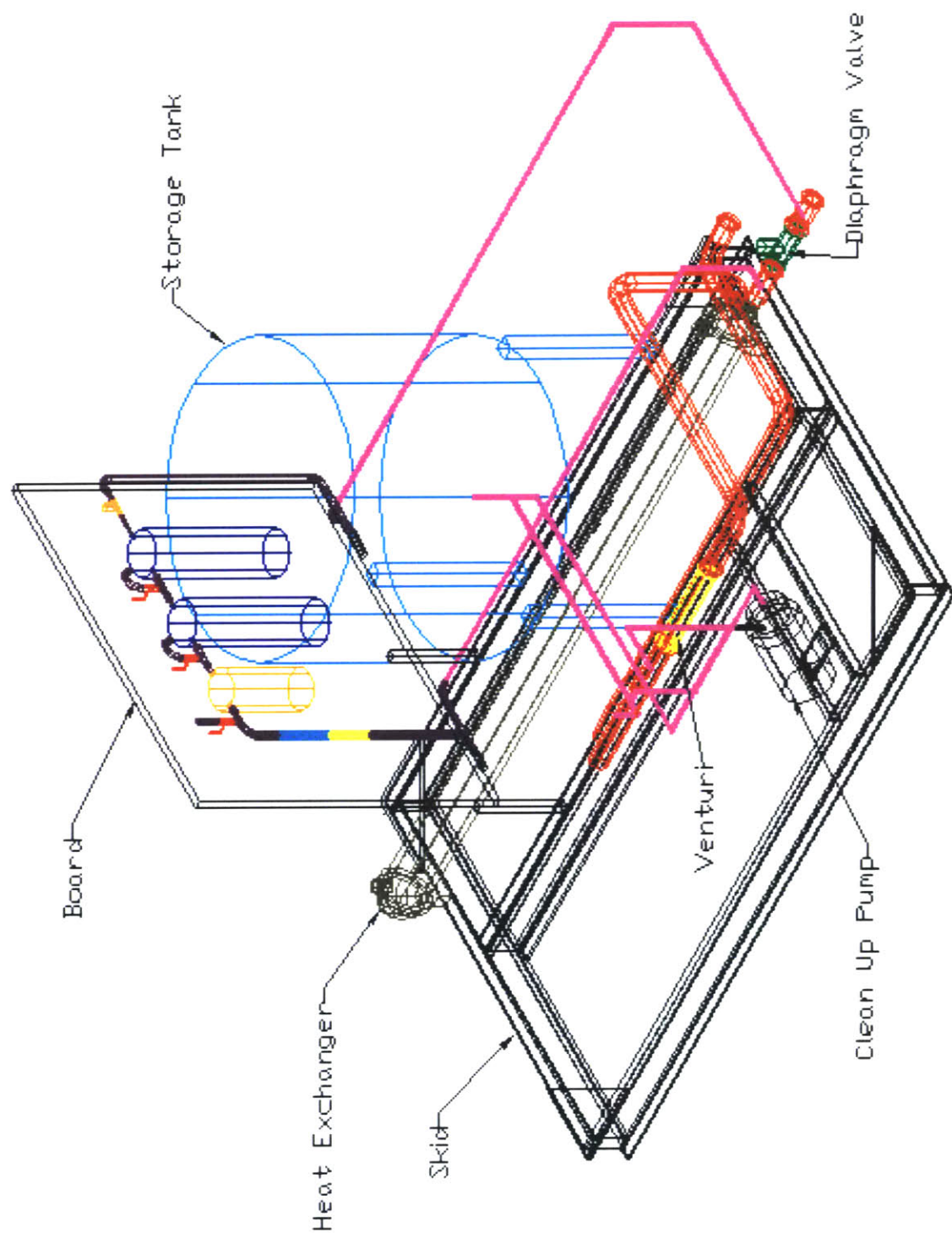


Figure 2-7. The layout diagram of clean up system.

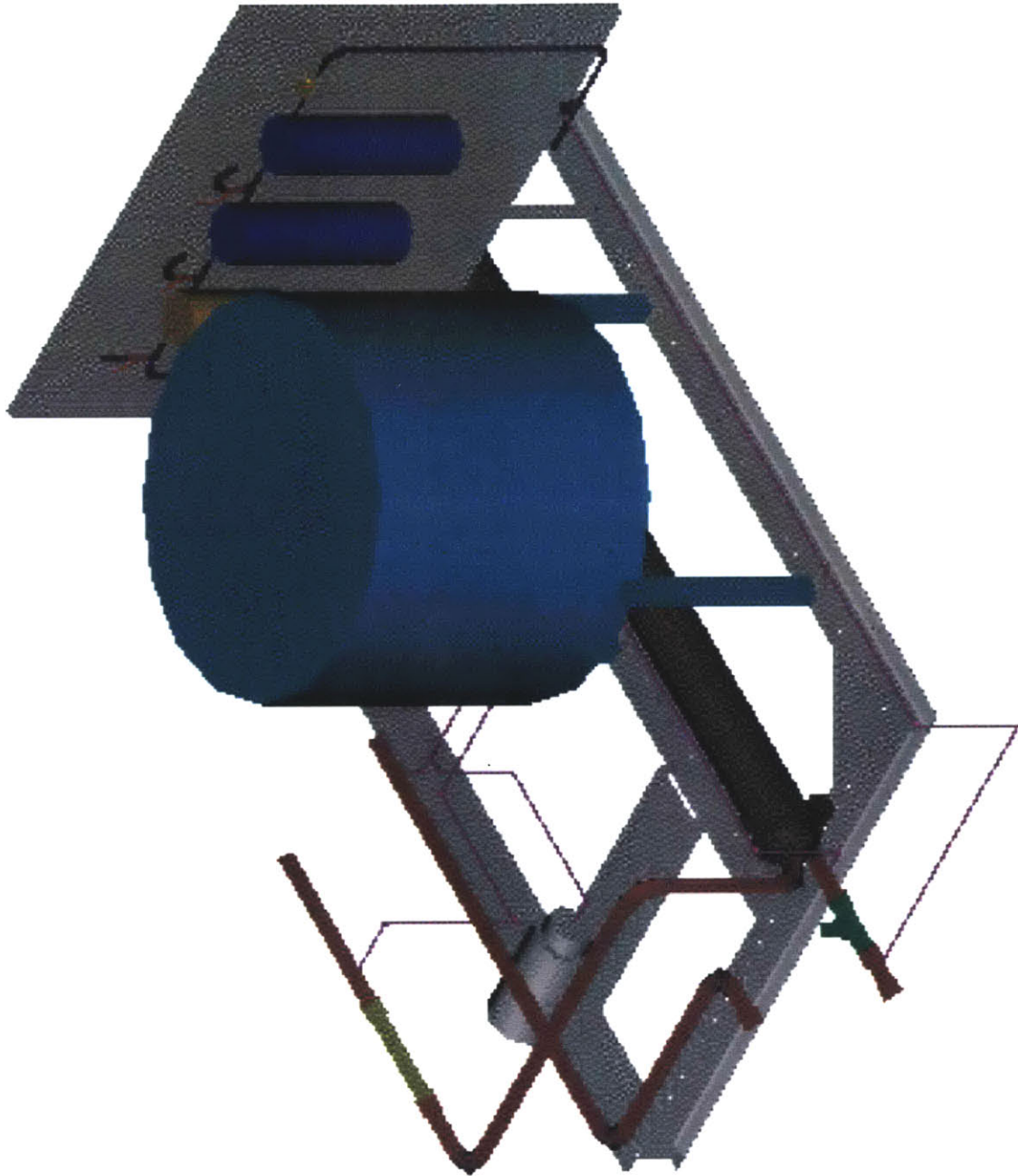


Figure 2-8. Solid diagram of clean up system.

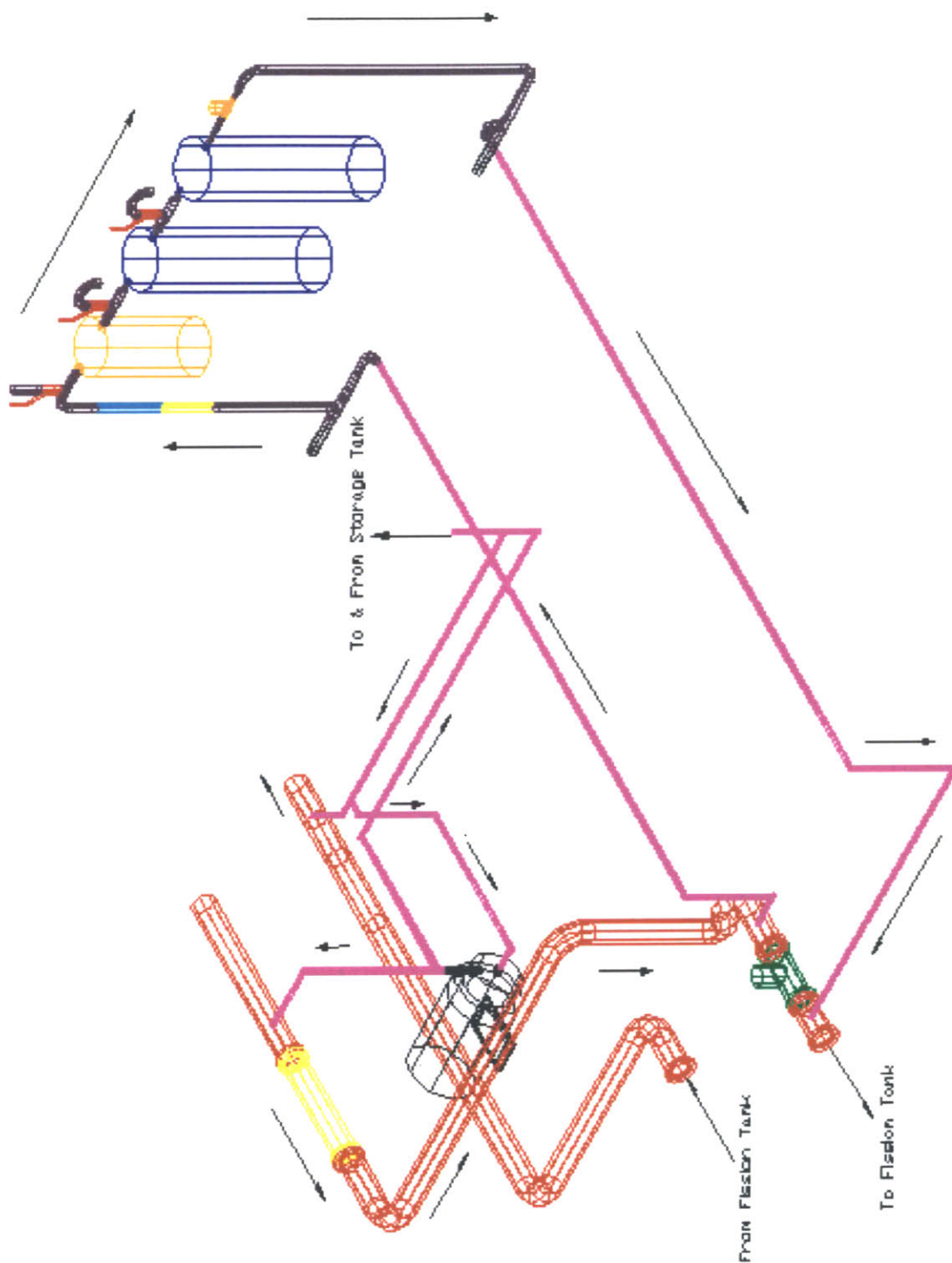


Figure 2-9. Flow diagram of clean up system.

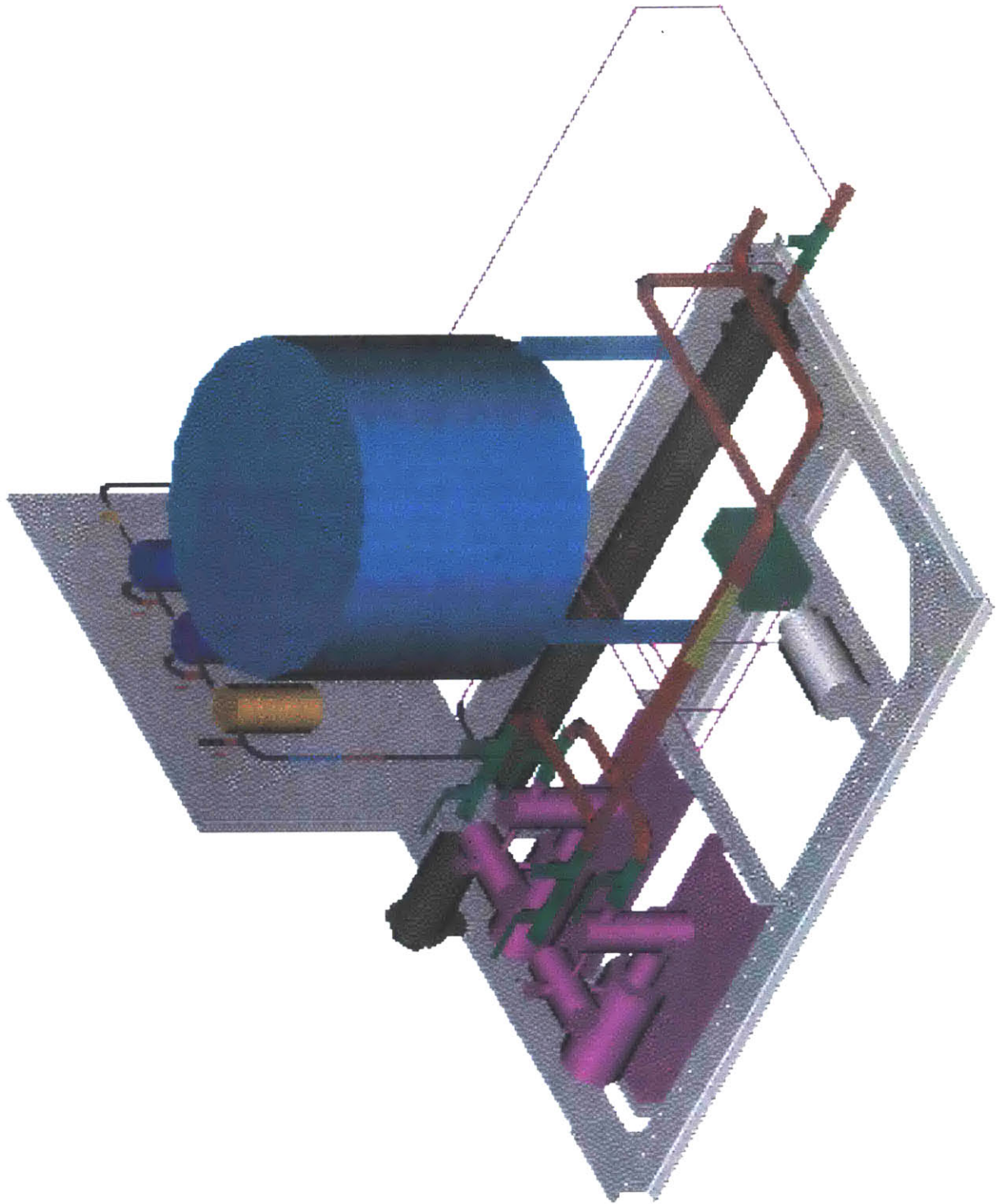


Figure 2-10. Solid layout of both primary system and clean up system.

2.2 ANALYSIS

2.2.1 Analysis of Initial Volume of Coolant

For initial startup of the system, the fission converter tank will be filled with the water, leaving only about an inch of gap from the top of the fission converter tank. Thus for the initial startup, the volume of the coolant should be approximately 0.73 m^3 or 193 gallons. Further analysis was done to estimate how far the coolant level in the fission converter tank will drop after the pumping system had been started. Assuming that the heat exchanger, two primary pumps, clean up pump, inlet and outlet ion column filters, ion exchanger, tubing, piping, and fittings are filled, the volume of the coolant left in the fission converter tank would be approximately 0.54 m^3 or 144 gallons. Therefore, the height of the coolant inside the fission converter tank will be about 17 inches from the top of the fission converter tank.

2.2.2 Analysis of Heat Exchanger

This analysis was divided into two portions. The first one was to find the temperature difference across the tube side of the heat exchanger. The second one was to find the approximate inlet and outlet temperatures of the tube side of the heat exchanger. The first step was to find the percentage increase of the overall heat transfer rate if the flow rate were to be increased from 50-50 GPM (50 GPM in the primary system and 50 GPM in the secondary system) to 67-76 GPM (67 GPM in the primary system and 76 GPM in the secondary system). From the properties of the coolant and stainless steel³, the percentage increase was found to be 28% by using these equations^{4,5} :

$$Re_D = \frac{(v)(D)}{\nu},$$

$$Nu_D = 0.023(Re_D)^{4/5} (Pr)^{0.3},$$

$$h_i = \frac{k}{D} Nu_D,$$

$$\frac{1}{U} = \frac{1}{h_o} + R_f + \frac{1}{h_i},$$

where :

v is the velocity in m/s,

D is the inner diameter of the tube in m,

Re is the Reynold's Number,

ν is kinematic viscosity in m^2/s ,

Nu_D is the Nusselt Number,

Pr is the Prandtl Number,

k is the thermal conductivity in W/m K,

U is the overall heat transfer coefficient in $W/m^2 K$,

R_f is the fouling factor in $m^2 K/ W$,

h is the heat transfer coefficient in $W/m^2 K$,

Subscript o represents the secondary system,

Subscript i represents the primary system.

The overall heat transfer rate of the heat exchanger at 67-76 GPM was calculated to be 2980 W/m² K.

Then by using equation^{4,5} :

$$Q_i = \dot{m}_i C_{p_i} \Delta T_i,$$

where :

Q is the heat produced in W,

m is the mass flow rate in kg/s,

C_p is the specific heat at constant pressure in J/kg K,

ΔT is the temperature difference in K,

Subscript i represents the primary system,

the temperature difference was found to be 10^0 C.

For the second part of the analysis, the following relations for 4-pass, cross-flow heat exchanger were used^{4,5} :

$$Q_{HX} = UA\Delta T_{HX},$$

$$\Delta T_{HX,CF} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)},$$

$$\Delta T_{HX} = F\Delta T_{HX,CF},$$

$$\Delta T_2 = T_{H,o} - T_{C,i},$$

$$\Delta T_1 = T_{H,i} - T_{C,o},$$

where :

Q is the heat in W,

U is the overall heat transfer coefficient in $\text{W/m}^2 \text{ K}$,

A is the surface area in m^2 ,

ΔT is the temperature difference in K,

F is the correction factor,

T is the temperature in K,

Subscript HX represents the heat exchanger,

Subscript CF represents the cross flow,

Subscript H represents hot side (primary system),

Subscript C represents cold side (secondary system),

Subscript i and o represent inlet and outlet respectively.

Using Mathcad 7 for the computation, the inlet temperature on the tube side of the heat exchanger was estimated at 49°C with an outlet temperature of 39°C . It was assumed that 200 kW of heat are generated in the fuel and the inlet temperature of the secondary system coolant is 30°C . The physical properties of the coolant were taken to be those at 40°C .

2.2.3 Analysis of Heat Loss in the Primary System Piping

The main purpose of this analysis was determine the potential error in evaluating the primary coolant core outlet temperature by measuring the temperature at the system skid, approximately 12 feet from the fission converter tank. Assuming smooth tubes and knowing the properties of heavy water³, stainless steel³, and air³, these equations were used^{4,5}:

$$\text{Re}_D = \frac{\rho U_m D}{\mu},$$

$$f = (1.82 \log \text{Re}_D - 1.64)^{-2},$$

$$\text{Nu}_{D, \text{Coolant}} = \frac{\left(\frac{f}{8}\right) \text{Re}_D \text{Pr}}{1.07 + 12.7 \left(\frac{f}{8}\right)^{\frac{1}{2}} (\text{Pr}^{\frac{2}{3}} - 1)},$$

$$\text{Ra}_D = \frac{\beta \Delta T_{air} g L^3}{\nu \alpha},$$

$$\text{Nu}_{D, air} = 0.48 \text{Ra}_D^{0.25},$$

$$h = \frac{\text{Nu}_D k}{D},$$

$$R_{tot} = \frac{1}{2\pi r_1 L h} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k L} + \frac{1}{h_{air} 2\pi r_2 L},$$

$$Q = \frac{(\Delta T_{air})}{R_{tot}},$$

$$Q = \dot{m} c_p \Delta T,$$

where :

Re is the Reynold's Number,

U_m is the velocity in m/s,

ρ is the density in kg/m^3 ,

D is the diameter of the pipe in m,

μ is the dynamic viscosity in $\text{kg/m} \cdot \text{s}$,

f is the fouling factor,

Pr is the Prandtl Number,

Nu is the Nusselt Number,

Ra is the Rayleigh Number,

g is the gravity in m/s^2 ,

ΔT is the temperature difference in K,

β is thermal coefficient in K^{-1} ,

L is the length of pipe in m,

ν is kinematic viscosity in m^2/s ,

α is thermal diffusivity in m^2/s ,

h is the heat transfer coefficient in $\text{W/m}^2\text{K}$,

k is the thermal conductivity in W/m K ,

R is the thermal resistance in K/W ,

r is the radius of the pipe in m,

Q is the heat in W,

\dot{m} is the mass flow rate in kg/s ,

c_p is the specific heat in J/kg K .

The temperature difference from the tank outlet to the skid was calculated to be only about 0.01°C . Therefore, the temperature can be accurately determined by measuring at the skid.

2.3 PRIMARY PUMP

The specifications of the primary pumps are tabulated below :

Table 2-1. Primary pump data.

Manufacturer	R.S. Corcoran Co. 500 North Vine Street New Lenox, IL 60451-0429 1-800-637-1067
Model	2000 Series D-SP(AB)
Type	Self-Primer, Close Coupled
Material of Construction	316 Stainless Steel
Pumping Application	55 GPM at 40 ft of head
Suction	2 in. FF FL (150#)
Discharge	2 in. FF FL (150#)
Mechanical Seal Size	0.750 in.
Mechanical Seal Type	2006-21DEP
Mechanical Seal Rotating Face	Carbon
Mechanical Seal Stationary Face	Silicon Carbide
Mechanical Seal Elastomer	EPDM
Mechanical Seal Metal Parts	316 Stainless Steel
Motor	1.5 HP, 3450 RPM, 208-230/460 V, 3 PH 60 Hz
Weight	200 lb.
Price	\$ 2600.00

The schematic of the primary pump is shown in Figure 2-11 while the pump curve is shown in Figure 2-12.

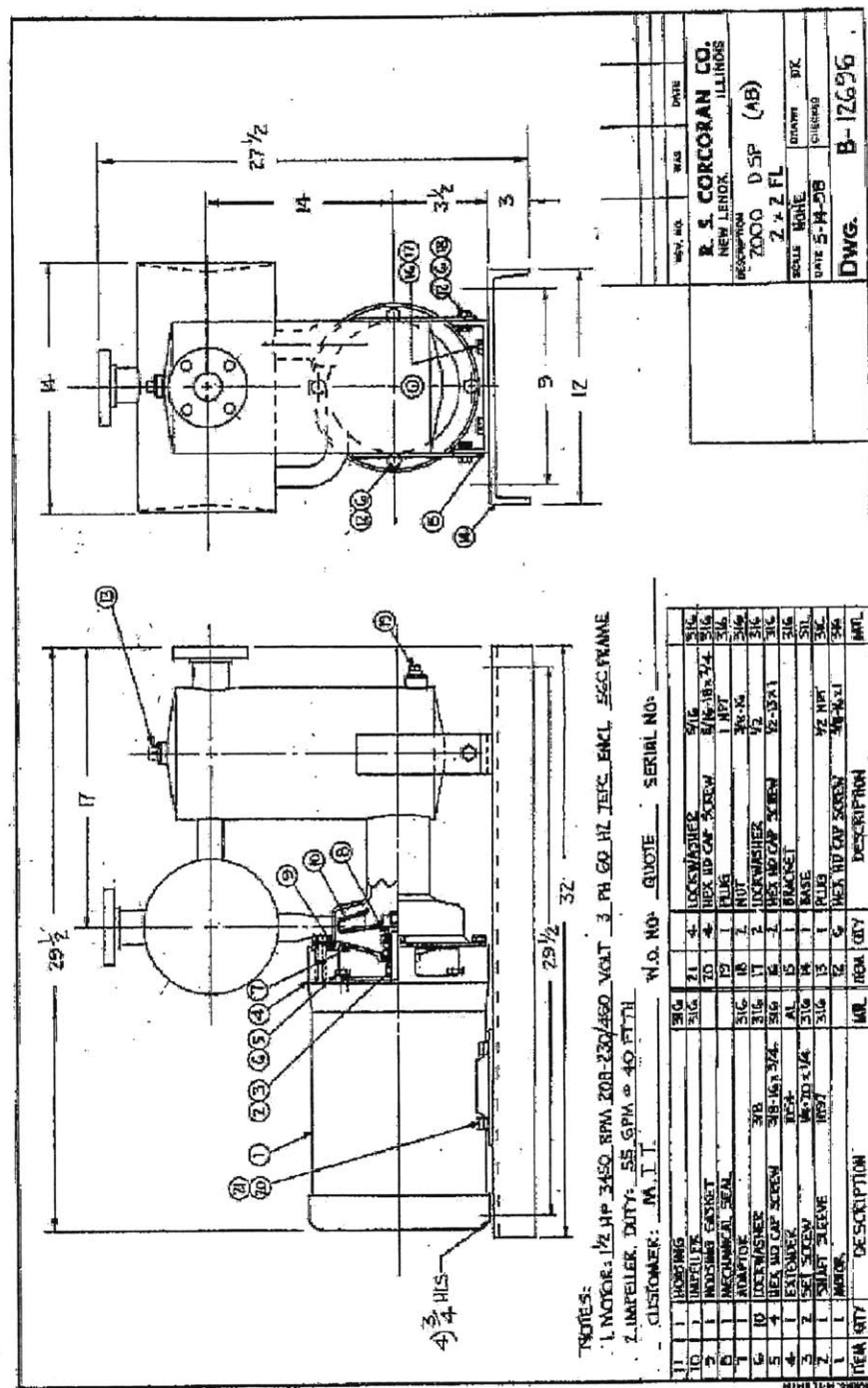


Figure 2-11. The schematic diagram of primary pump.



**R.S.
CORCORAN Co.**

500 NORTH VINE STREET
P.O. BOX 429
NEW LENOX, IL 60451-0429

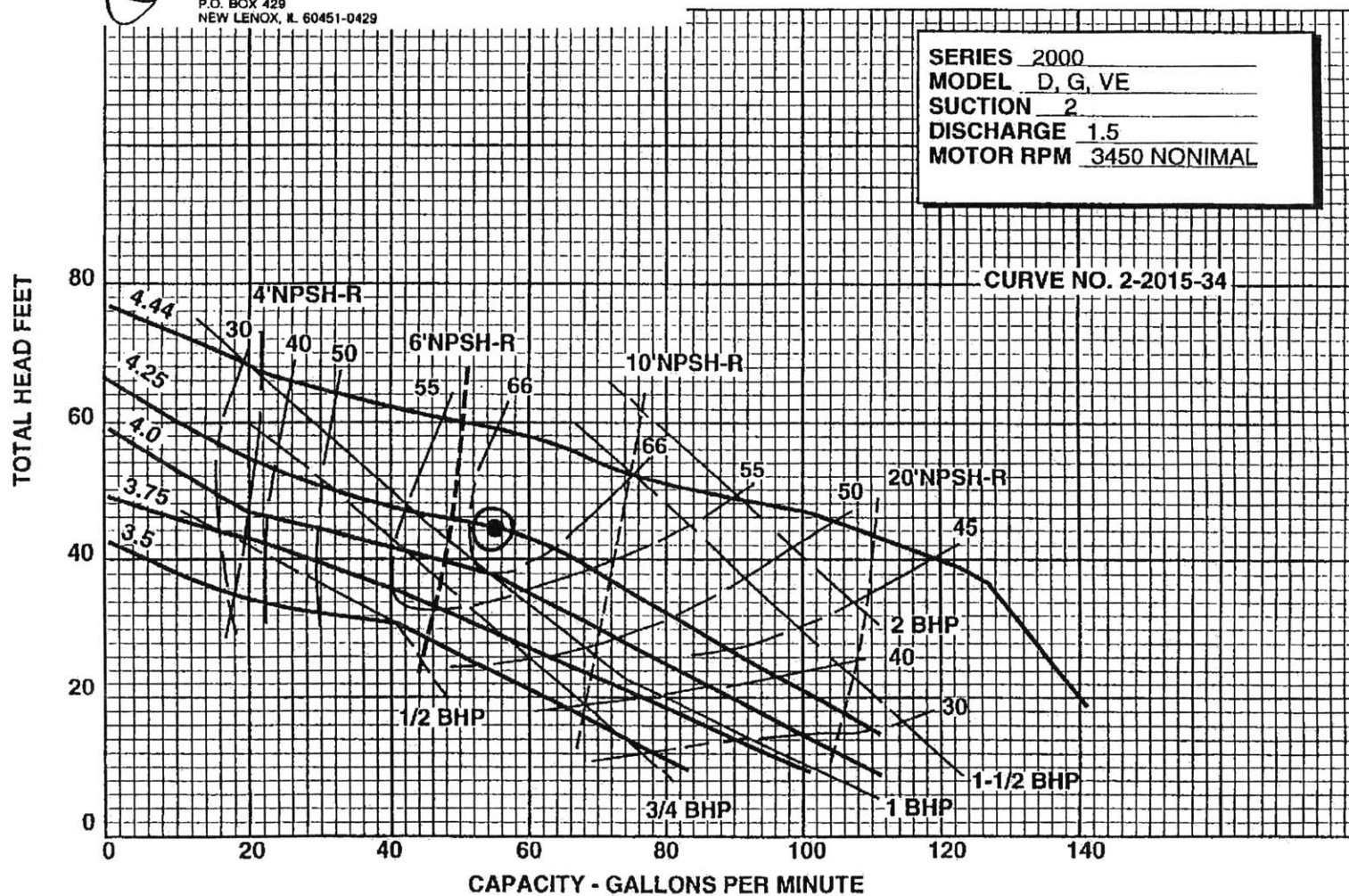


Figure 2-12. Pump curve for the primary pump.

2.4 HEAT EXCHANGER

The specifications for the heat exchanger are tabulated below :

Table 2-2. Heat exchanger data.

ITT STANDARD		Heat Exchanger	
Buffalo, New York 14240		Specification sheet	
1		Job No.	
2	Customer MIT	Reference No.	
3	Address	Inquiry No. T598-3R1	
4	Plant location	Date 5-11-98 SMT	
5	Service of unit	Item No. 1	
6	Size 06096 SX2000 Type	Connected in	
7	Sq.ft.Surf/unit 91.1	Shells/unit 1.	Sq.ft.Surf/shell 91.1
PERFORMANCE OF ONE UNIT			
8		Shell Side	Tube Side
9		WATER	
10	Fluid circulated		
11	Total fluid entering lbs/hr	24927.	28070.
12	Vapor		
13	Liquid gpm	50.	50.
14	Steam lbs/hr		
15	Non-condensables		
16	Fluid vaporized or condensed lbs/hr		
17	Steam condensed		
18	Density lb/cu.ft.	61.979	70.000
19	Viscosity centipoise	0.67	0.61
20	Molecular weight		
21	Specific heat BTU/lb-deg F	0.998	0.999
22	Thermal conductivity BTU/hr-ft-deg F	0.363	0.374
23	Latent heat BTU/lb		
24	Temperature in deg F	86.00	140.00
25	Temperature out deg F	115.70	113.65
26	Operating pressure psig		
27	No. of passes per shell		2
28	Velocity ft/sec	2.68	3.21
29	Pressure drop psi	6.02	1.98
30	Fouling resistance (min.) hr-ft ² -F/WTU	0.0000	0.0005
31	Heat exchanged - BTU/hr 738800	MTD Corrected-deg F	19.73
32	Transfer rate - BTU/hr-ft ² -F Service	410.98	Clean
CONSTRUCTION OF ONE SHELL			
33			
34	Design pressure psig	300.	150.
35	Test pressure psig	450.	225.
36	Design temperature deg F	300.	300.
37	Tubeside 3/6 WLD S/S #Holes 116 OD 3/8 BWG 24 Lgth 96 Pch 29/64 TRI.		
38	Shell STEEL I.D. O.D.	Shell cover	
39	Channel or Bonnet 3/6 S/S	Channel cover	
40	Tubesheet-stationary 3/6 S/S	Tubesheet-floating	
41	Baffles-cross STEEL Type SEG	Floating head cover	
42	Baffles-long Type	Impingment protection	
43	Tube supports		
44	Tube to tubesheet joint ROLLED		
45	Gaskets COMPRESSED FIBER		
46	Connections-shell side in 2.00 Out 2.00	Rating P.T.	
47	Channel side in 2.00 Out 2.00	Rating P.T.	
48	Corrosion allowance-shell side	Tube side	
49	Code requirements	TEMA Class	
50	Weights-each shell	Bundle	Full of water
51			
52	Remarks PHYSICAL PROPERTIES ARE AT MEAN TEMPERATURE		
53			
54			
55			

DESIGN DATA

DESIGN PRESSURE		TEST PRESSURE		DESIGN TEMPERATURE	
TUBESIDE	150 PSI	225 PSI	225 PSI	450 °F	450 °F
SHELLSIDE	225 PSI	338 PSI	338 PSI	450 °F	450 °F
MIN. DESIGN METAL TEMP.		WET WEIGHT		DRY WEIGHT	
-20 °F		285 LBS.		193 LBS.	

REVISIONS

ITEM NO.	QUANTITY	DESCRIPTION	MATERIAL & SPEC.	SIZES / PATTERNS NO.	ALL DIMENSIONS ARE IN INCHES	DATE
1	1	CORE ASSEMBLY				
2	1	FOAMER				
3	1	FOAMER				
4	1	FOAMER				
5	1	CASKET				
6	2	SUPPORT FOOT				
7	2	PIR PLUGS				
8	12	CAPSCREW				
9	4	CAPSCREW				

REVISIONS

REV.	DATE	DESCRIPTION
1	5-03-2	06-096 SSC-K EXCHANGER - 1 PASS

Standard
Buffalo, NY U.S.A.

06096 SSC-K EXCHANGER - 1 PASS

5-03-2-06-096-001

40

2.5 CLEAN UP PUMP

The specifications for the clean up pump are tabulated below :

Table 2-3. Clean up pump data.

Manufacturer	R.S.Corcoran Co.
Model	2000 Series D (AA05)
Type	Close Coupled Centrifugal
Material of Construction	316 Stainless Steel
Pumping Application	1 GPM at 23 ft
Suction	¾ in. FNPT
Discharge	½ in. FNPT
Mechanical Seal Size	0.750
Mechanical Seal Type	2006-2140EP
Mechanical Seal Rotating Face	Carbon
Mechanical Seal Stationary Face	Silicon Carbide
Mechanical Seal Elastomer	EPDM
Mechanical Seal Metal Parts	316 Stainless Steel
Motor	1/6 HP,1750 RPM, 115/208-230 V, 1 PH 60 Hz
Weight	45 lb.
Price	\$ 764.00

The schematic diagram of the clean up pump is given in Figure 2-14 and the pump curve is in Figure 2-15.

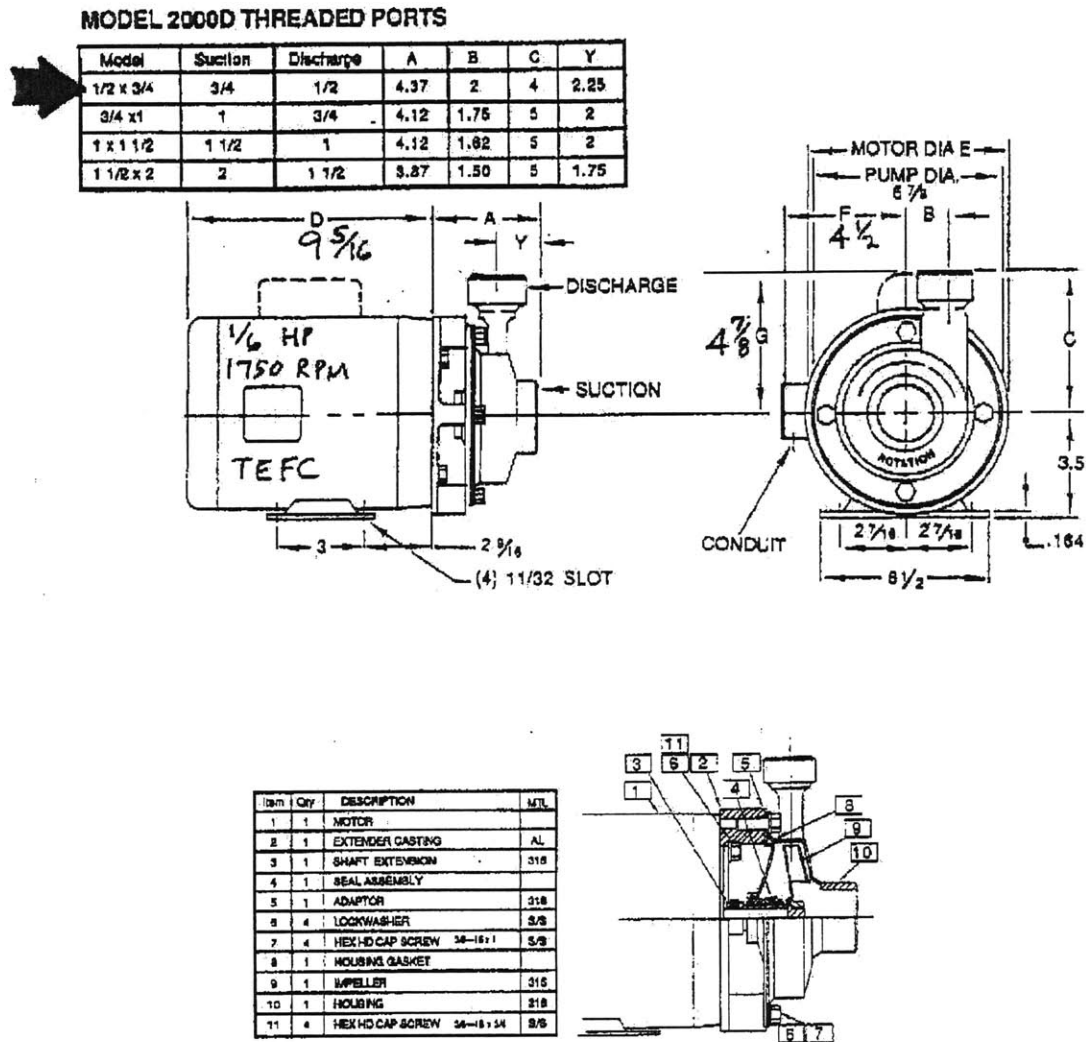


Figure 2-14. Schematic diagram of the clean up pump.



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NEW LENOX, IL. 60451-0429

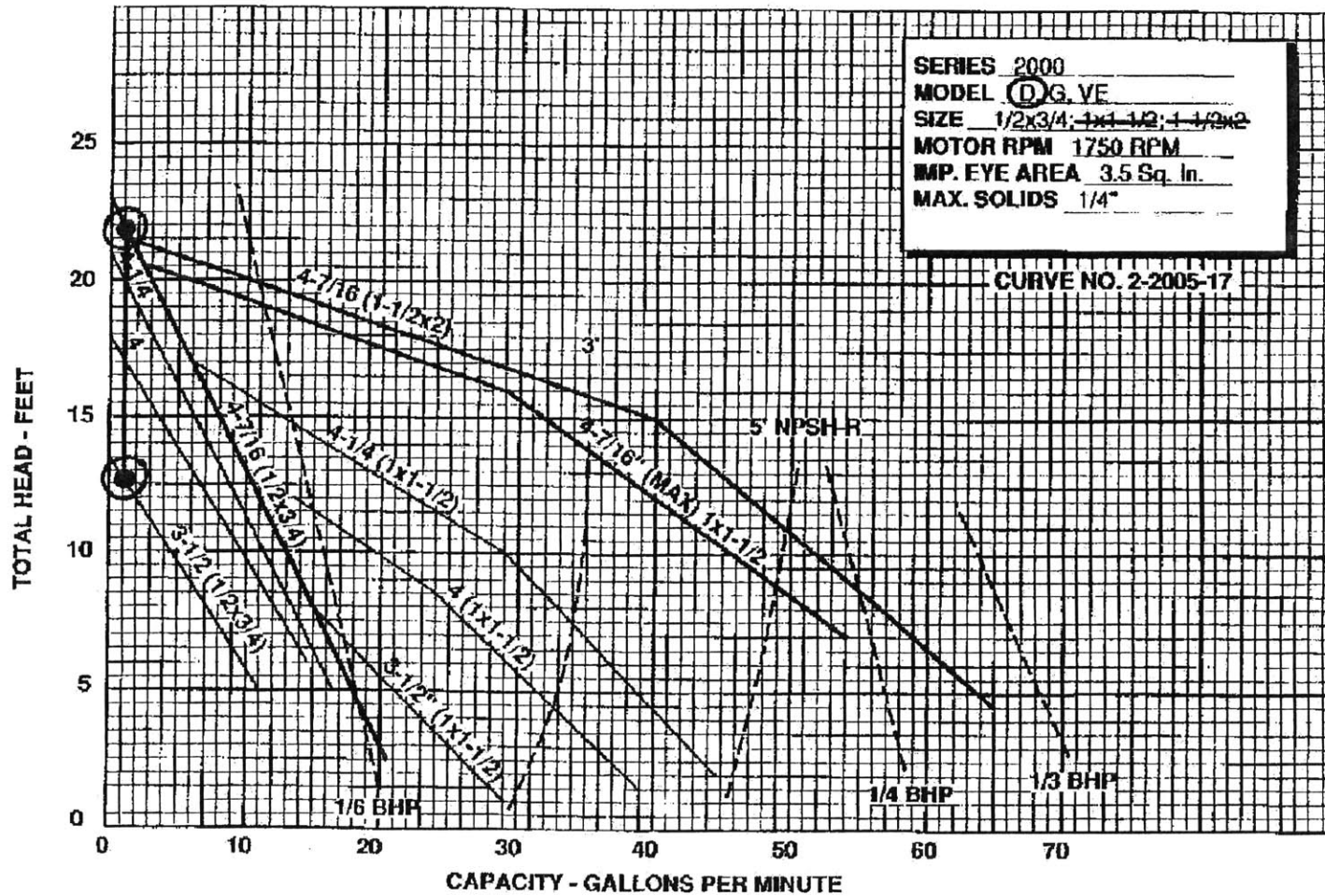


Figure 2-15. Pump curve for clean up pump.

2.6 SKID

The skid was made of 4 C-channels and an I-beam made of steel^{6,7}. The engineering drawing is shown in Figure 2-16.

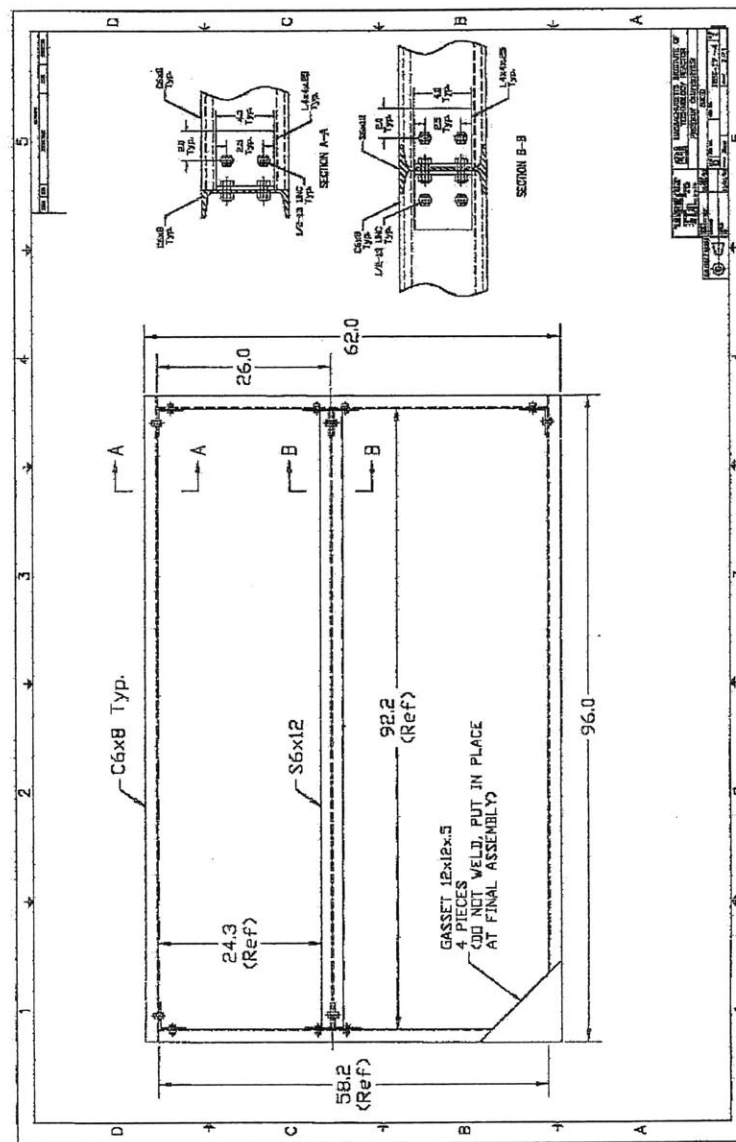


Figure 2-16. Engineering drawing of the skid (Courtesy of Y.Ostrovsky).

2.7 CONCLUSION

2.7.1 Primary System

The primary system and pumps curve is given in Figure 2-17.

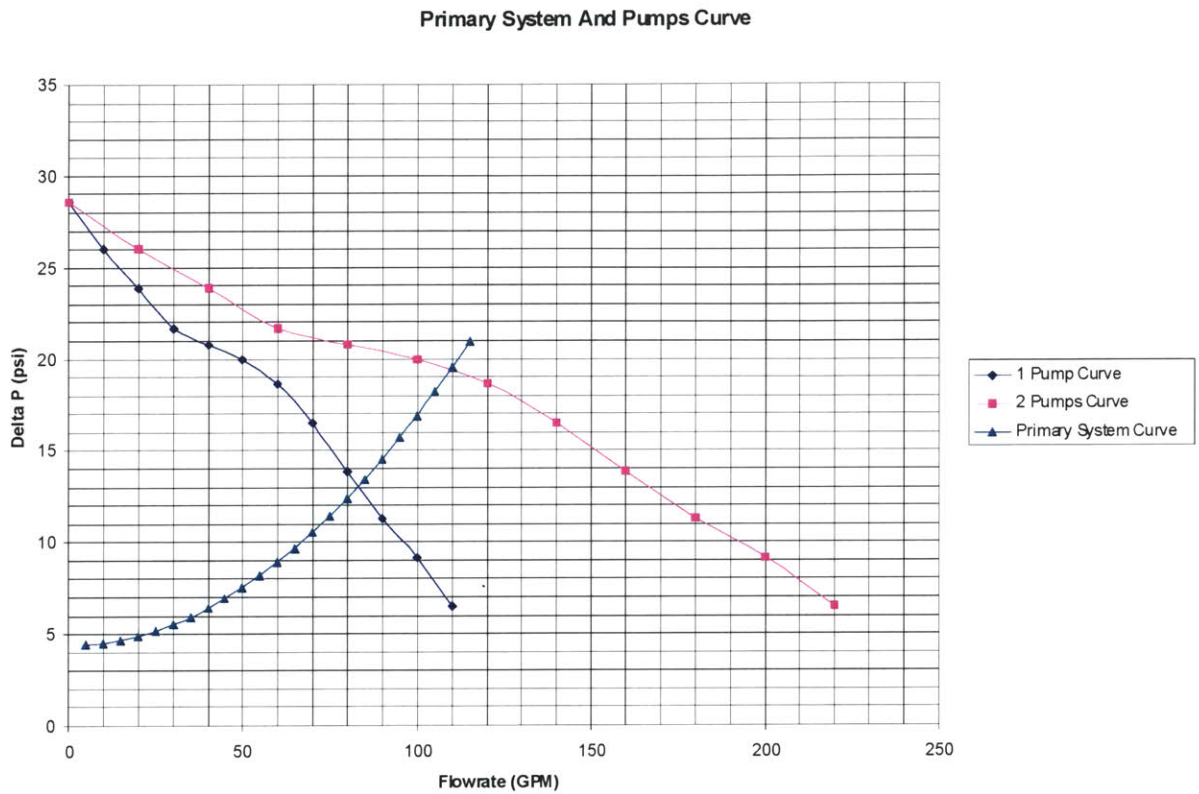


Figure 2-17. Graph of primary system and primary pump curve.

From this curve, the flow rate of the primary system can be estimated at 110 GPM with the differential pressure at 19.5 psi when both primary pumps are running. If only one pump is running, the flow rate is reduced to 84 GPM at 13 psi ΔP . Thus, even if only one pump is working, the flow rate is more than the design flow rate of 67 GPM. In the heat

exchanger analysis, it was shown that the estimated inlet and outlet temperatures of the heat exchanger in the primary system are 49°C and 39°C respectively, below the limiting temperature of 60°C . However, this analysis was done for a primary flow rate was at 67 GPM. At the expected higher flow rate, the heat transfer rate would be higher and the actual temperature of the primary system should be lower than the estimates above.

The temperature reading for the coolant in the fission converter tank can be made at the skid instead of at the exit of the fission converter tank since the heat loss through the piping between the two points is negligible.

For the initial volume of the coolant in the system, filling up the fission converter tank is acceptable since after the system is running, the water level will still be above the water level sensor.

2.7.2 Clean Up System

The system and pump curves for the clean up system are given in Figure 2-18.

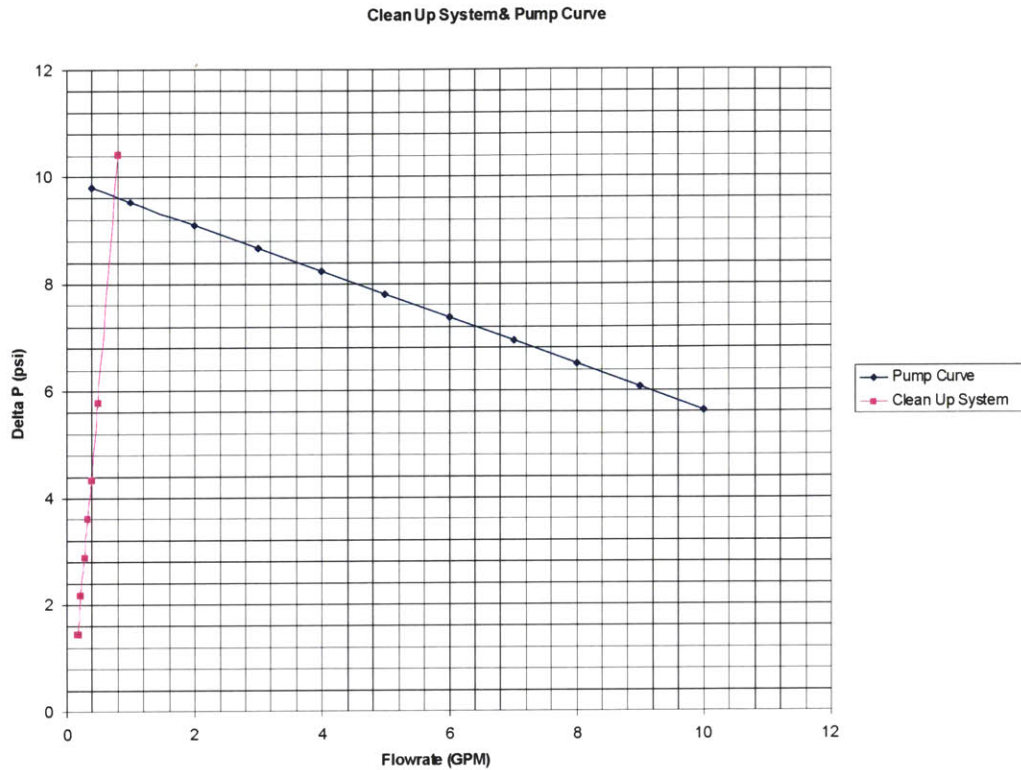


Figure 2-18. Graph of clean up system and clean up pump curve.

From this graph, the flow rate of the clean up system is expected to be 0.8 GPM at a differential pressure of 9.7 psi. In order to maintain the flow rate to that which is necessary for the decay heat removal, a diaphragm valve was installed between the inlet and outlet of the clean up system so that the flow can be bypassed.

2.8 REFERENCES

1. Sutharshan, B., *Engineering Design of a Fission Converter-Based Epithermal Beam for Neutron Capture Therapy*, Ph.D. Thesis, Massachusetts Institute of Technology, 1998.
2. Hu, L.W., Fission Converter SER Technical Specification, 1997.
3. Avallone, E.A., and Baumeister III, T., *Marks' Standard Handbook for Mechanical Engineers*, 10th Edition, Mc Graw-Hill, 1996.
4. Incropera, F.P., and De Witt, D.P., *Introduction to Heat Transfer*, 2nd Edition, John Wiley & Sons, 1990.
5. Mills, A.F., *Heat and Mass Transfer*, Richard D. Irwin, INC., 1995.
6. Hibbeler, R.C., *Engineering Mechanics Statistics and Dynamics*, 6th Edition, Macmillan Publishing Company, 1992.
7. Hibbeler, R.C., *Mechanics of Materials*, 2nd Edition, Prentice Hall, 1994.

CHAPTER 3

SECONDARY SYSTEM

3.1 INTRODUCTION

The secondary system consists of two pumps in parallel, copper piping, instrumentation such as pressure gauges, temperature gauges, and flow meter, and the shell side of the heat exchanger. The schematic diagram of the secondary system is shown in Figure 3-1. The reasoning behind having two pumps was to allow the patient irradiation to finish in case one of the pumps fails during the irradiation¹.

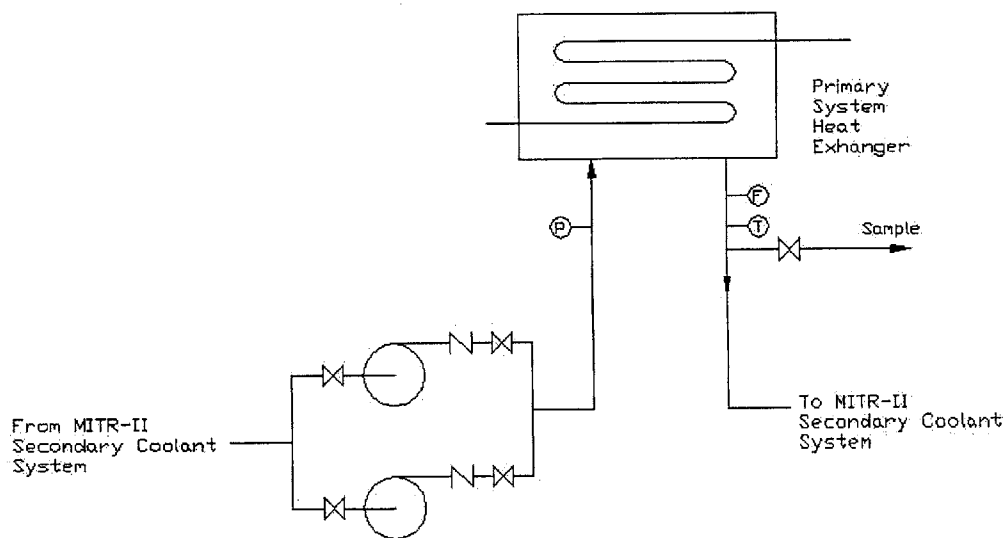


Figure 3-1. The schematic diagram of the secondary system.

The coolant in this system is light water (H_2O) from the secondary system of the MITR¹. Positive suction head at the pump inlet is provided by the reactor secondary pumps.

The secondary system will be located inside the equipment room of the MITR. The purpose of the system is to remove the heat from the primary system by using the heat exchanger². A diagram of the equipment room is shown in Figure 3-2 (the dotted box shows the proposed location for the secondary pumps) and the proposed design layout of the secondary system is shown in Figure 3-3 and the flow direction of the secondary system is shown in Figure 3-4.

Two inch diameter pipe will be used in this system. The pressure loss due to piping and fittings, the flow rate of the system, and the pump specifications are discussed later in this chapter.

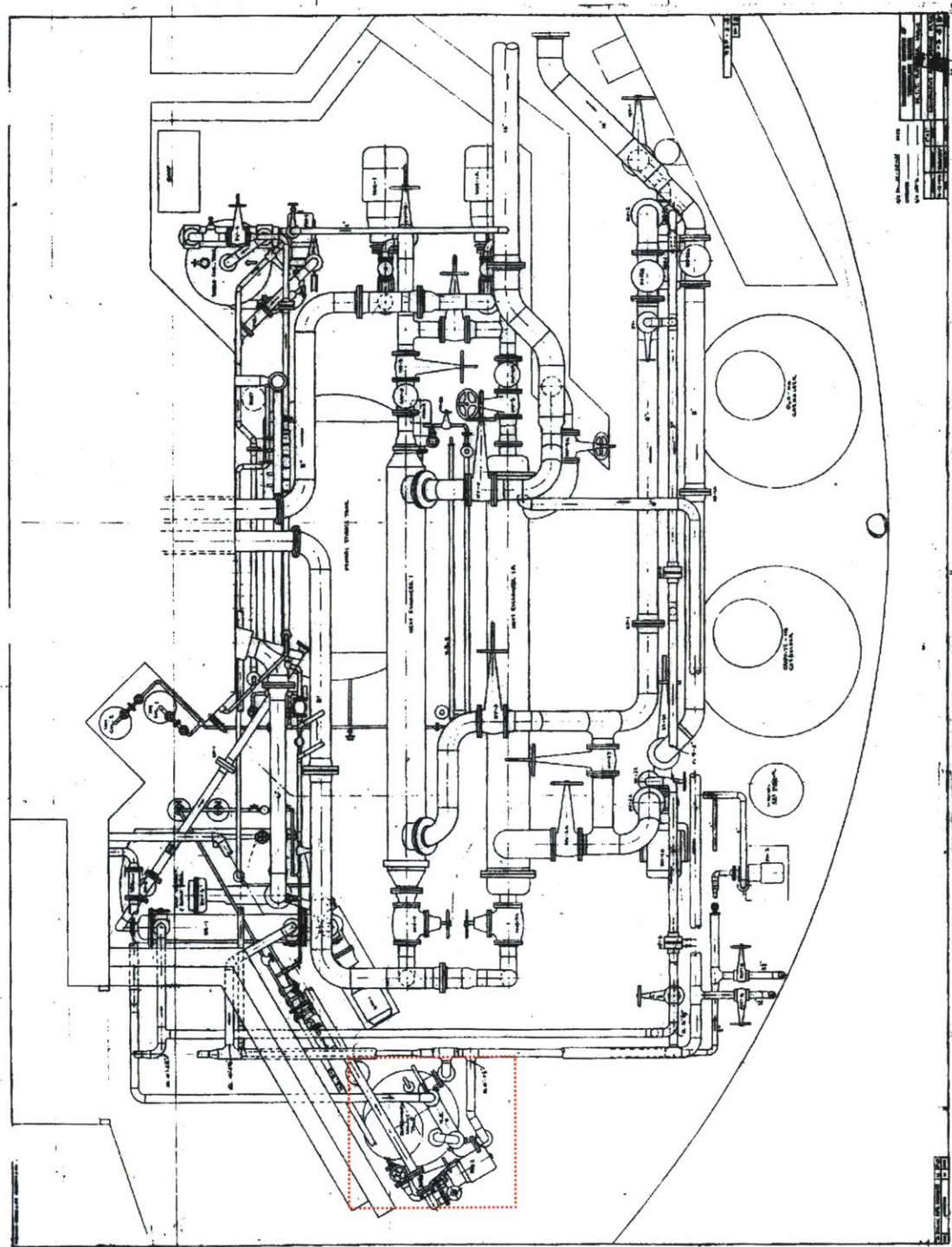


Figure 3-2. Top view of equipment room in the basement of the MITR.

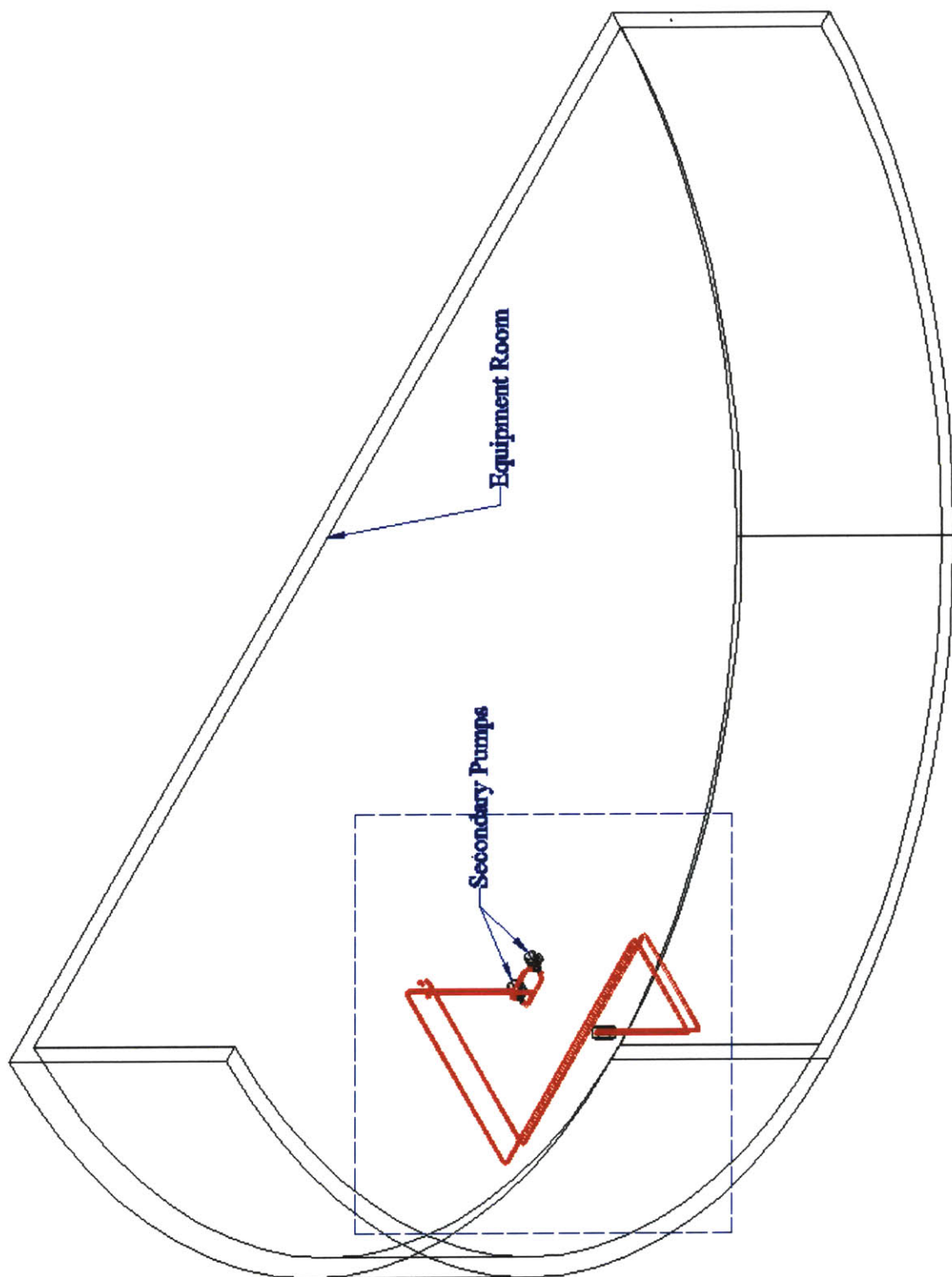


Figure 3-3. Isometric view of the secondary piping layout.

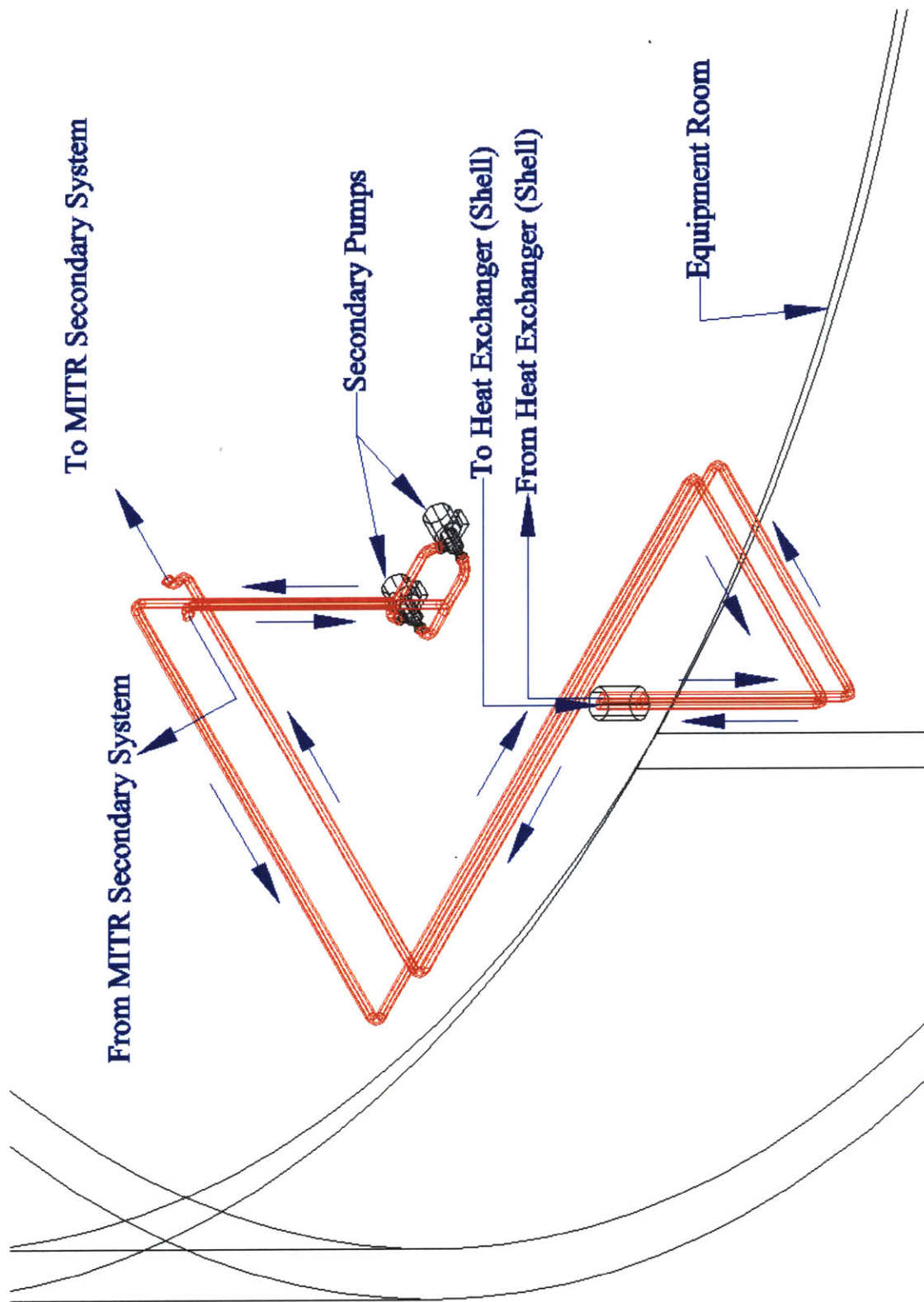


Figure 3-4. Flow direction of the secondary system (Dotted box in Fig 3.3).

3.2 ANALYSIS

3.2.1 Analysis of Flow Rate

The main purpose of this analysis was to find the flow rate needed in order to determine the specifications of the pump for the secondary system. An initial assumption for the temperature of the coolant had to be made for the analysis. Assuming that the reactor is working under normal conditions, the inlet temperature of the coolant will be 20⁰ C and the outlet temperature of the coolant will be 35⁰ C. The calculation was done for 300 kW heat rejected to provide safety margin. Using the equation shown^{3,4} :

$$m = \frac{W}{(Cp)(T_{out} - T_{in})},$$

where :

m is the mass flow rate in kg/s,

W is the heat produced in W,

Cp is the specific heat at constant pressure in J/kg K,

T_{out} is the outlet temperature of the coolant in K,

T_{in} is the inlet temperature of the coolant in K,

the flow rate needed was found to be 4.77 kg/s or approximately 76 GPM.

3.2.2 Analysis of Pressure Loss

From rough measurement of the placement of the secondary pumps relative to the heat exchanger on top of the medical room, it was estimated that the piping and fitting would consist of approximately 200 feet of straight pipe, and 20 long radius elbows. Furthermore, the height from the equipment room to the heat exchanger was

approximated at 25 feet. Having this data, the properties of water⁵, and the properties of the pipe⁵, the pressure drop across this piping could be found by using the moody chart and the equations below⁶:

$$v = \frac{m}{(\rho)(\pi/4)(D^2)},$$

$$Re = \frac{(v)(D)}{\nu},$$

$$k = f \frac{L}{D},$$

$$h = k \frac{v^2}{2g},$$

where :

v is the velocity in m/s,

m is the mass flow rate in kg/s,

ρ is the density in kg/m³,

D is the inner diameter of the pipe in m,

Re is the Reynold's Number,

ν is kinematic viscosity in m² / s,

k is the resistance coefficient,

f is the friction factor,

L is the length of the pipe in m,

g is the gravity in m/s²,

h is the pressure in m.

The pressure loss across the piping and the fittings was found to be approximately 4.4 m or 15 ft of water.

3.2.3 Analysis of Heat Exchanger (Shell Side)

For this analysis, the highest power operating condition of MITR was used. This condition would produce 200 kW of heat in the fission converter tank. The next step was to find the percentage increase of the overall heat transfer coefficient of the shell side of the heat exchanger if the flow was increased from 50-50 GPM to the design flow of 67-76 GPM. By using the properties of water and of the material used in the tube side of the heat exchanger⁵, the heat transfer coefficient of the heavy water on the primary side, and these equations below^{3,4} :

$$Re_D = \frac{(v)(D)}{\nu},$$

$$Nu_D = 0.023(Re_D)^{4/5}(Pr)^{0.4},$$

$$h_o = \frac{k}{D} Nu_D,$$

$$\frac{1}{U} = \frac{1}{h_o} + R_f + \frac{1}{h_i},$$

where :

v is the velocity in m/s,

D is the inner diameter of the shell in m,

Re is the Reynold's Number,

ν is kinematic viscosity in m^2/s ,

Nu_D is the Nusselt Number,

Pr is the Prandtl Number,

k is the thermal conductivity in W/m K,

U is the overall heat transfer coefficient in $W/m^2 K$,

R_f is the fouling factor in $m^2 K/ W$,

h is the heat tranfer coefficient in $W/m^2 K$,

Subscript o represents the secondary system,

Subscript i represents the primary system,

the percentage increase was found to be 28 %. Therefore, the overall heat transfer coefficient for a flow of 67-76 GPM can be estimated as 2980 $W/m^2 K$, based on manufacturer's data for the 50-50 GPM design flows.

The worst case condition also assumed that the inlet temperature of the water is 30⁰ C. Thus, with this equation^{3,4} :

$$Q_o = m_o C p_o \Delta T_o,$$

where :

Q is the heat produced in W,

m is the mass flow rate in kg/s,

Cp is the specific heat at constant pressure in J/kg K,

ΔT is the temperature difference in K,

Subscript o represents the secondary system ,

the temperature difference between the inlet and outlet of the heat exchanger on the secondary side was found to be 10⁰ C.

3.2.4 Analysis of Secondary Pump Failure

A failure of one pump would cause the flow to drop to 59 GPM. In this analysis, an assumption of constant temperature difference was made. By using the similar basic equations shown above, it was determined that if both primary pumps were operational, the temperature increase due to this failure in the secondary system would be 1.4°C/s . At this rate, the primary system will reach critical temperature of 60°C from the starting temperature of 40°C in approximately 14 minutes. However, if only one primary pump is operational, the temperature increase rate is 1.8°C/s . At this rate, the increase from 40°C to 60°C occurs in approximately 11 minutes. An additional analysis was made for the case of 250 kW. With this amount of heat, the temperature rate is 3.0°C/s if both primary pumps are working and 3.9°C if only one primary pump is working. Thus the time for the primary system to reach 60°C when initially at 40°C would be roughly 7 minutes and 5 minutes respectively.

3.2.5 Analysis of Secondary System Failure

Two analyses were made. First, it was assumed that no secondary coolant flow is present (pipe breaks or blockage). Second, the case of both fission converter pumps failing but flow continuing to be driven by the reactor secondary flow was evaluated. In the latter case, a pressure difference of about 3 psi is expected to generate a mass flow rate of 2.4 kg/s.

For the analysis, this equation was used^{3,4} :

$$\frac{\Delta T}{t} = \frac{Q}{Mc_p},$$

where :

ΔT is the temperature difference in K on the primary side of the heat exchanger,

t is the time in second,

Q is the heat in W,

M is the mass in kg,

c_p is the specific heat in J/kg K.

For no flow in the secondary system, the results are tabulated below:

Table 3-1. Temperature increase on primary side over time without secondary flow and with primary pumps operating.

Q	100 kW	200 kW	300 kW
$\frac{\Delta T}{t}$	1.8° C/min	3.5° C/min	5.3° C/min

For the second part of the analysis, since there was flow in the secondary system, some of the heat was being removed. The results are tabulated below:

Table 3-2. Temperature increase on primary side over time without secondary pumps but with primary pumps operating.

Q	100 kW	200 kW	300 kW
$\frac{\Delta T}{t}$	None	3.1° C/min	3.3° C/min

3.3 SECONDARY PUMPS

As the analysis of the pressure loss shows, the drop in pressure across the piping and fittings is 4.4 m or 15 ft of water. The pressure difference between the two points where the fission converter secondary system is attached to the secondary system of the MITR is only about 3 psi (approximately 2.1 m or 6.9 ft). Thus, it is necessary to provide fission converter secondary pumping. The secondary pumps should provide 76 GPM against ΔP of 15 ft of water. However, quotes for secondary pumps were acquired before these analyses and pumps capable of 50 GPM against of 20 ft of water were requested. It had also been decided that two pumps were required for this system. The quotes on this secondary pump are summarized in Table 3.1 :

Table 3-3. Summary of secondary pump quotes which can pump 50 GPM at 20 ft of water.

<u>Manufacturer</u>	<u>Type</u>	<u>Price</u>	<u>Delivery Time</u>
Warrender, LTD	Seal-less Mag-Drive	\$ 402.00	1-3 days
Advanced Pump Company	Centrifugal	\$ 309.00	2-3 days
OTT Process Equipment	Centrifugal	\$ 753.00	1 week
N.M. Fales, Inc.	Centrifugal	\$ 787.00	1-2 weeks

3.4 CONCLUSION

From the analysis of the pressure loss across the piping and fittings, the system curve could be estimated. Furthermore, using the pump curve from the pump manufactured by Warrender, LTD and the estimated system curve, the flow rate of the secondary system and its operating pressure can be found for conditions where two pumps are operational or just one is operational. The system curve and the pump curve are shown below :

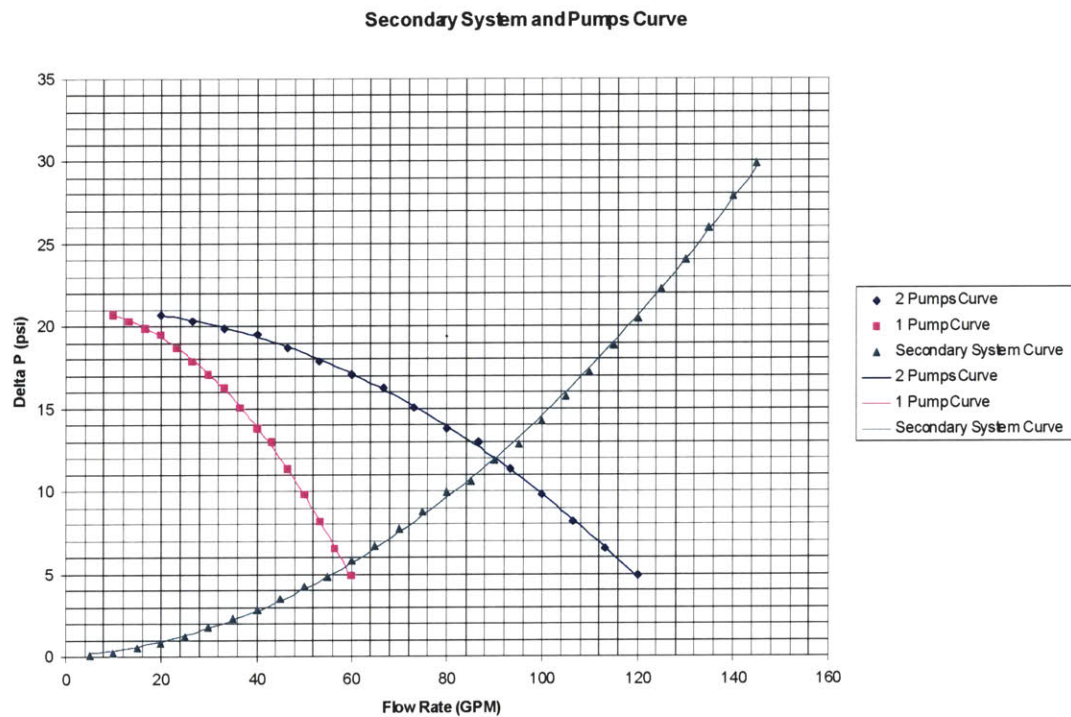


Figure 3-5. Graph of secondary system and the pump curve.

From the figure, with two pumps operating, the flow rate of the system will be 90 GPM at a ΔP of 12 psi. If only one pump is operating, the flow rate of the system will be 59 GPM at a ΔP of 5.5 psi.

The flow rate of the system if only one pump is operating does not meet the required flow rate to take the heat out of the primary system. However, from the analysis done, having just one pump operational might be enough to finish an irradiation. This is because with one secondary pump operating and two primary pumps operating, it should keep the temperature of the primary side below 60°C for approximately 14 minutes assuming the converter power is 200 kW. Unfortunately, having only one pump operational, starting up a new irradiation is not recommended.

3.5 REFERENCES

1. Sutharshan, B., *Engineering Design of a Fission Converter-Based Epithermal Beam for Neutron Capture Therapy*, Ph.D. Thesis, Massachusetts Institute of Technology, 1998.
2. Hu, L.W., Fission Converter SER Technical Specification, 1997.
3. Mills, A.F., *Heat and Mass Transfer*, Richard D. Irwin, INC., 1995.
4. Incropera, F.P., and De Witt, D.P., *Introduction to Heat Transfer*, 2nd Edition, John Wiley & Sons, 1990
5. Avallone, E.A., and Baumeister III, T., *Marks' Standard Handbook for Mechanical Engineers*, 10th Edition, Mc Graw-Hill, 1996.
6. Roberson, J.A., and Crowe, C.T., *Engineering Fluid Mechanics*, 5th Edition, Houghton Mifflin Company, 1993.

CHAPTER 4

COVER GAS SYSTEM

4.1 INTRODUCTION

The cover gas system consists of a blower, tubing and fittings made out of stainless steel, recombiner, and the storage tank¹. The purpose of this system is to exclude air from the fission converter coolant and cover gas spaces and to permit gas sampling². Helium cover gas pressure will be controlled between 1 and 5 psi by a feed and bleed system, which would feed helium gas into the fission converter tank if the pressure went below 1 psi and would bleed the helium gas if the pressure exceeded 5 psi. Helium gas will be supplied from a pressurized tank with regulator.

The schematic diagram of this system is shown in Figure 4-1¹. All the components of this system would sit on the same skid as the primary system as shown in Figures 4-2 and 4-3. The flow diagram of this system is shown in Figure 4-4.

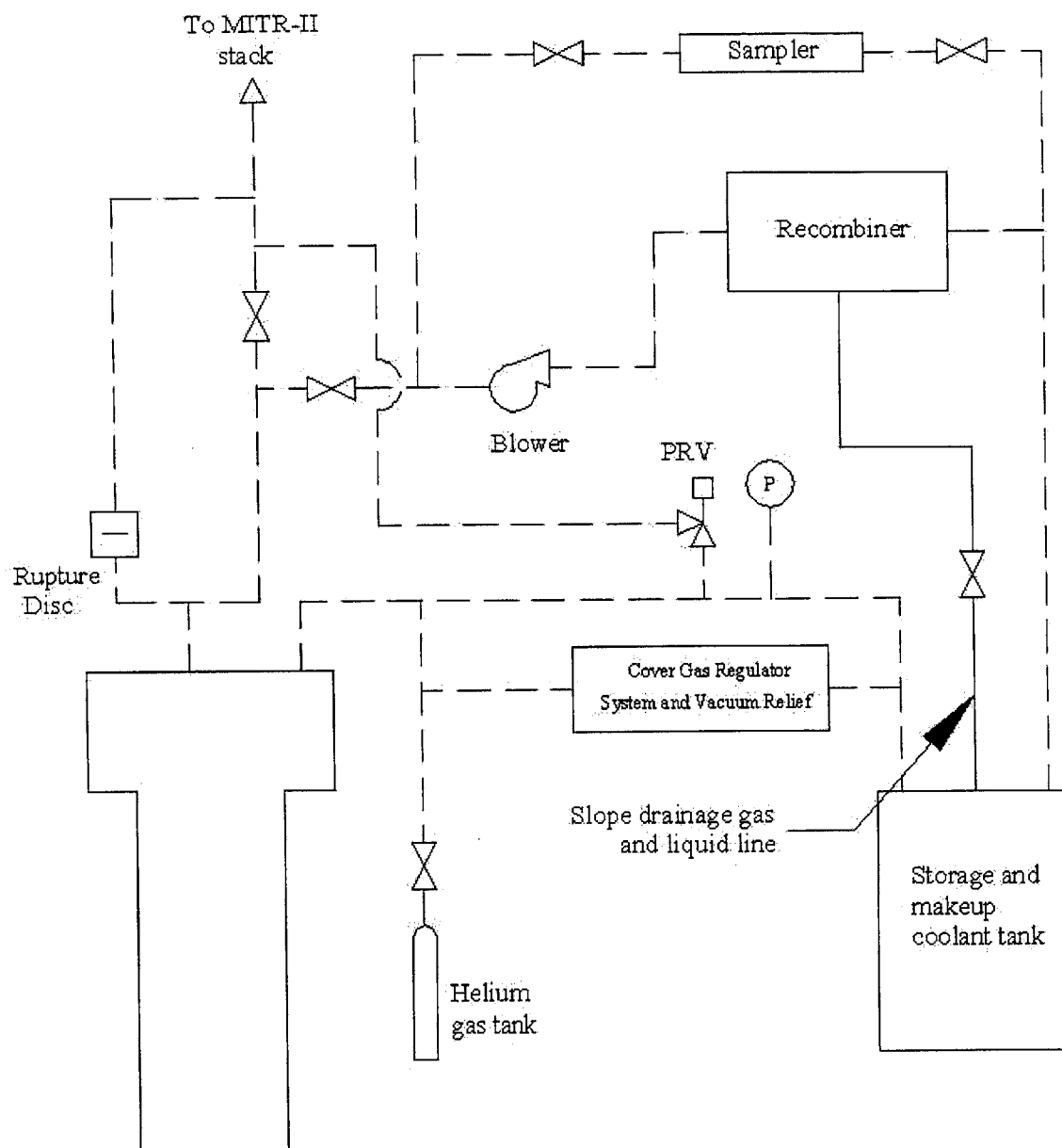


Figure 4-1. Schematic diagram of cover gas system.

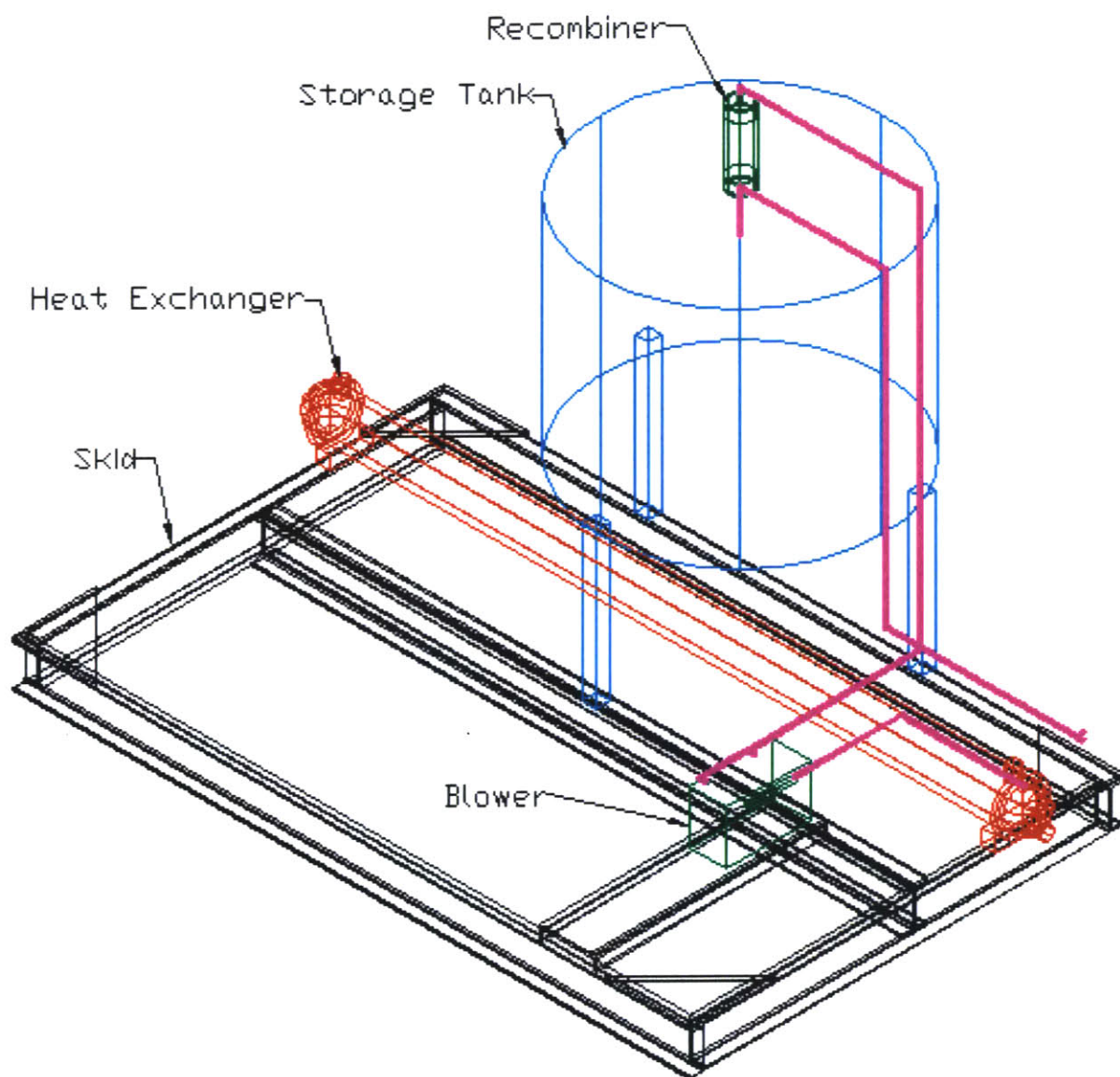


Figure 4-2. Layout diagram of cover gas system.

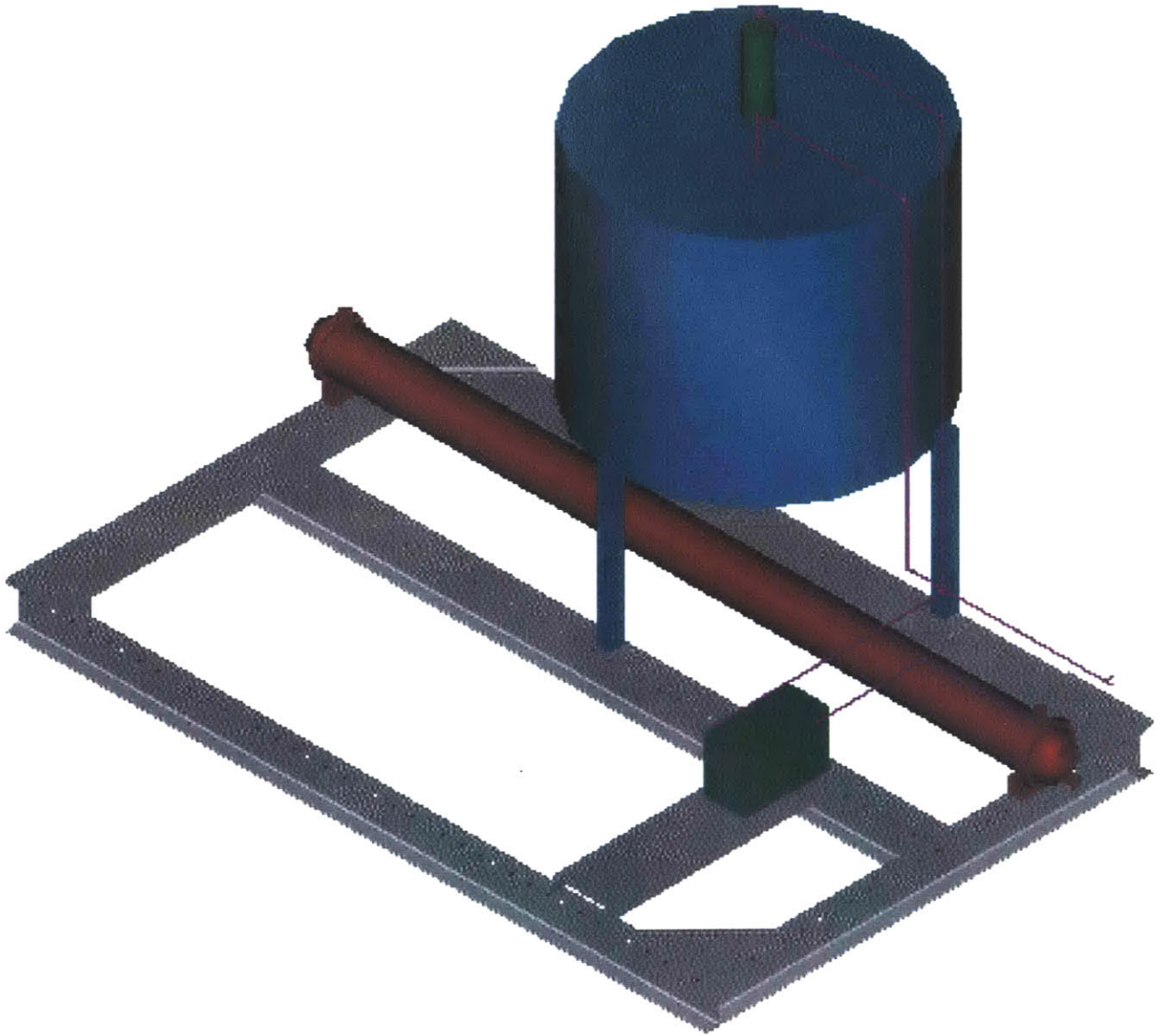


Figure 4-3. Solid diagram of cover gas system.

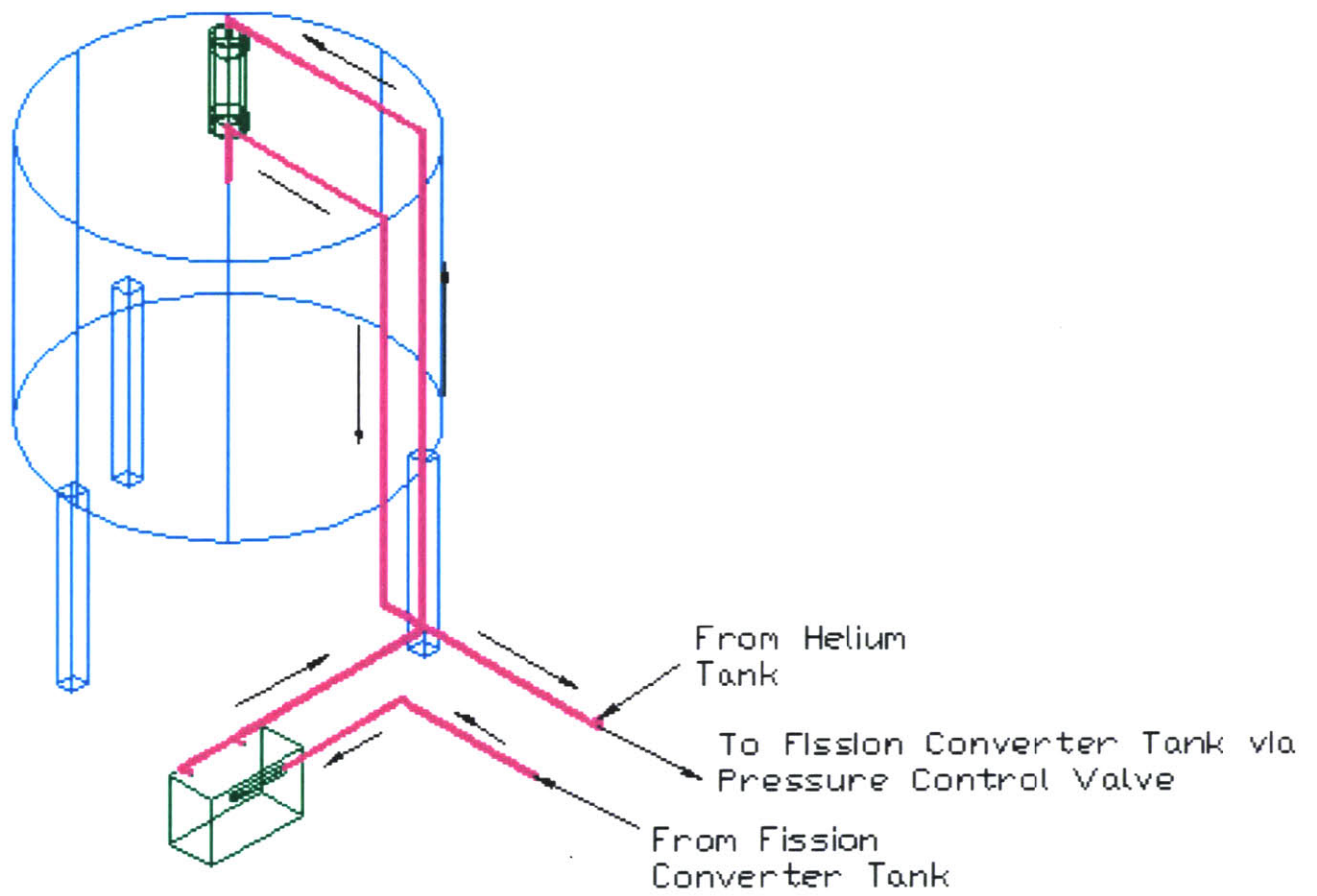


Figure 4-4. The flow diagram of cover gas system.

4.2 ANALYSIS

4.2.1 Analysis of the Pressure Change in the Cover Gas as a Result of the Thermal Expansion of the Heavy Water

This analysis was done in order to find out what the increase in pressure is when the coolant inside the fission converter tank is heated by the fuel elements. This is critical because it would be undesirable to have the feed and bleed system operating continuously. The analysis was done using the ideal gas equation³:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2},$$

where :

P is the pressure in N/m^2 ,

V is the volume in m^3 ,

T is the temperature in K,

Subscripts 1 and 2 represent state 1 and 2,

and this equation for the expansion of the coolant³:

$$\Delta V = m(v_{T1} - v_{T2}),$$

where :

ΔV is the change in volume in m^3 ,

m is the mass in kg,

v is the specific gravity in m^3/kg ,

Subscripts T1 and T2 represent temperature at states 1 and 2 respectively.

By assuming that the temperature of the helium gas remained constant, and with data for the properties of heavy water⁴, the increase in pressure was found to be approximately 0.01 psi.

4.2.2 Analysis of Thermal Expansion of Helium Gas

This analysis was to find out what the pressure increase would be due to the thermal expansion of the helium gas itself. By using the same equations and data as in 4.2.1, and also by assuming that the temperature increased from 20°C to 50°C , the pressure of the helium gas turned out to be approximately 1.1 psi.

4.3 GAS BLOWER

The design specification for the cover gas blower calls for a flow rate of 1 cfm. A diaphragm gas blower manufactured by GAST is used in this system. The specifications for this blower are tabulated in Table 4-1.

Table 4-1. Specifications of the GAST diaphragm gas blower for the cover gas system.

Max. Pressure	60 psi.
Max. Open Flow	2.4 cfm
Motor	110V/115V-50Hz/60Hz-1 Phase
Motor Type	PSC (4 Pole)
RPM at 60 Hz	1575
RPM at 50 Hz	1275
HP	0.25
kW	0.19
AMPS	3.6/3.5
Capacitor	04 mfd – 370 V
Sound Level	< 70 dBA
Net Weight	28lb. (12.7 kg)
Price	\$386.00

The blower performance chart is shown in Figure 4-5 and a drawing of the blower is shown in Figure 4-6.

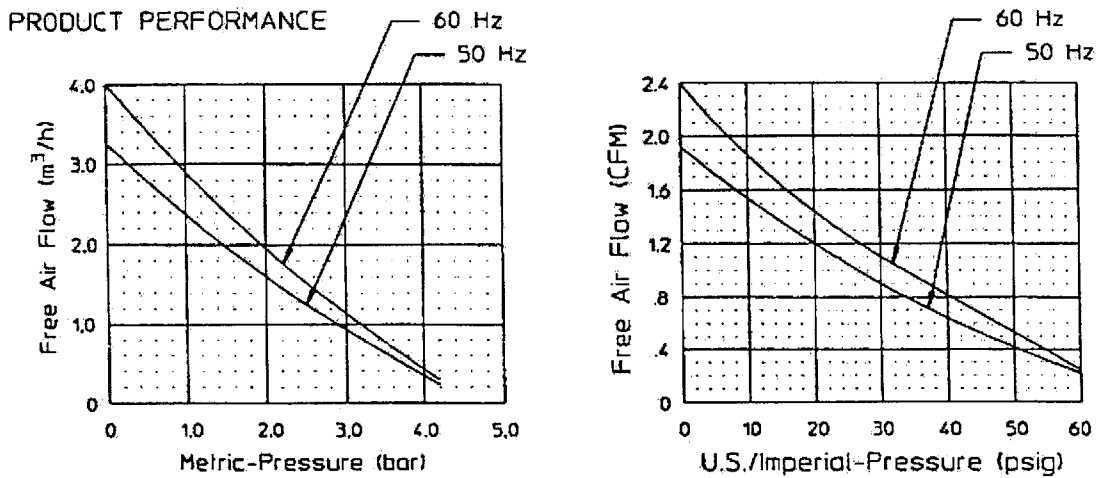


Figure 4-5. Performance curves for the gas blower.

NOTES:

1. ALL DIMENSIONS ARE FOR REFERENCE USE ONLY.
2. PRODUCT DIMENSIONS: U.S. IMPERIAL (inches) METRIC (mm).
3. ■ = TECHNICAL DATA SUBJECT TO CHANGE WITHOUT NOTICE.
4. INSTALLATION: THIS PUMP MUST BE INSTALLED IN AN ENCLOSURE.

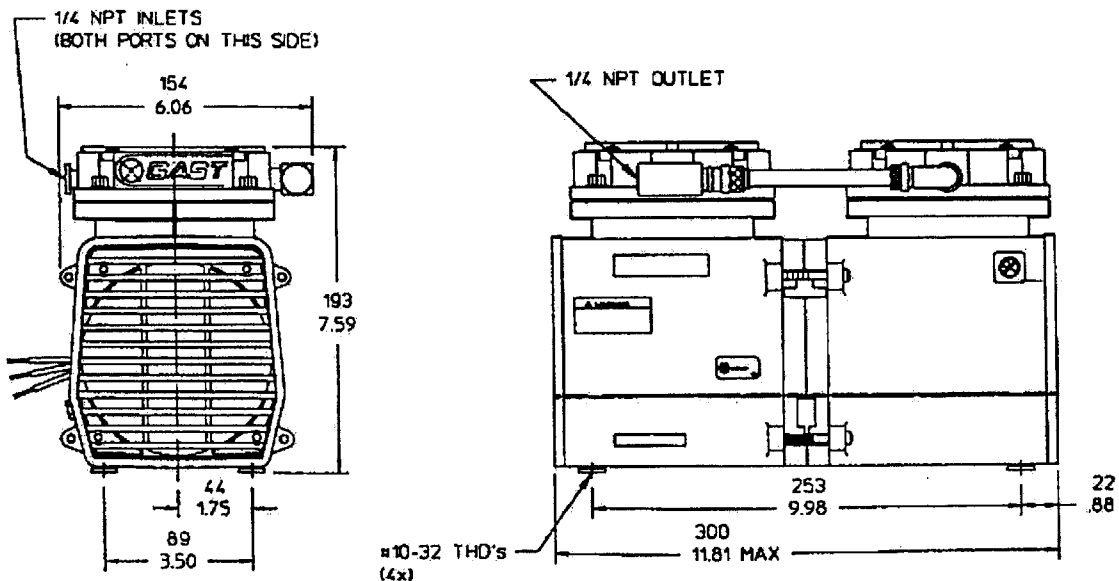


Figure 4-6. Manufacturer's drawing of the GAST gas blower.

4.4 CONCLUSION

It is evident from the performance curves that the required flow of 1 cfm can be delivered at a pressure up to 35 psi. The blower will fit easily on the skid without obstructing the main piping and components.

The increase in pressure of the helium gas due to thermal expansion of the gas and the coolant was small, thus the feed and bleed system should work well in this cover gas system.

4.5 REFERENCES

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CHAPTER 5

HEAT REMOVAL SYSTEM

5.1 SUMMARY

The heat removal system is composed of several different sub-systems. With a flow rate of 110 GPM on the primary side and 76 GPM on the secondary side, the heat removal capability of this system is calculated to exceed the requirements. Furthermore, the analyses of the capabilities of the heat removal system during normal conditions and worst case conditions proved that this heat removal system will work in all these conditions and meets the requirements and the design specifications.

The current status of the heat removal system is as follows. Most of the major components except for the storage tank had been placed on the steel skid. Moreover, most of the primary piping on the skid is in placed and has been welded. For the clean up system and cover gas system, only the clean up pump and the blower have been put in placed.

Future work for the heat removal system includes the completion of the piping and, component installation of the clean up system, the purchasing of secondary pumps, components, and piping and the installation of the secondary system, the purchasing of cover gas components, and tubing and installment of the cover gas system. The placement of the heat removal system on the new medical room and

testing the heat removal system will be the last steps towards completing this project.

Analysis of the N-16 dose in the system is recommended.

The layout of the heat removal system with respect to the medical room and the fission converter tank is shown in Figures 5-1 and 5-2.

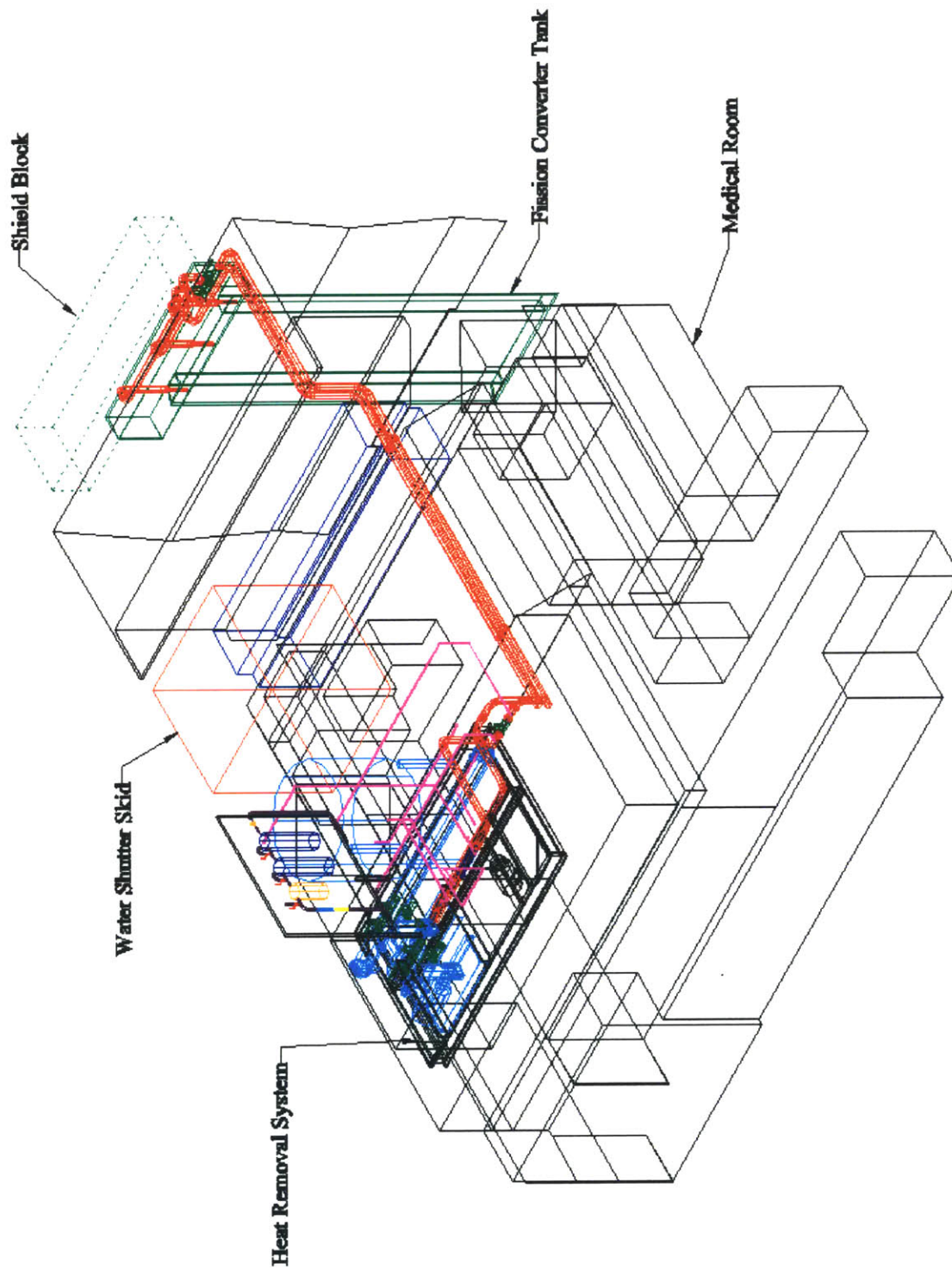


Figure 5-1. Layout diagram of heat removal system on the roof of medical room
(scale 1 in. : 64 in.).

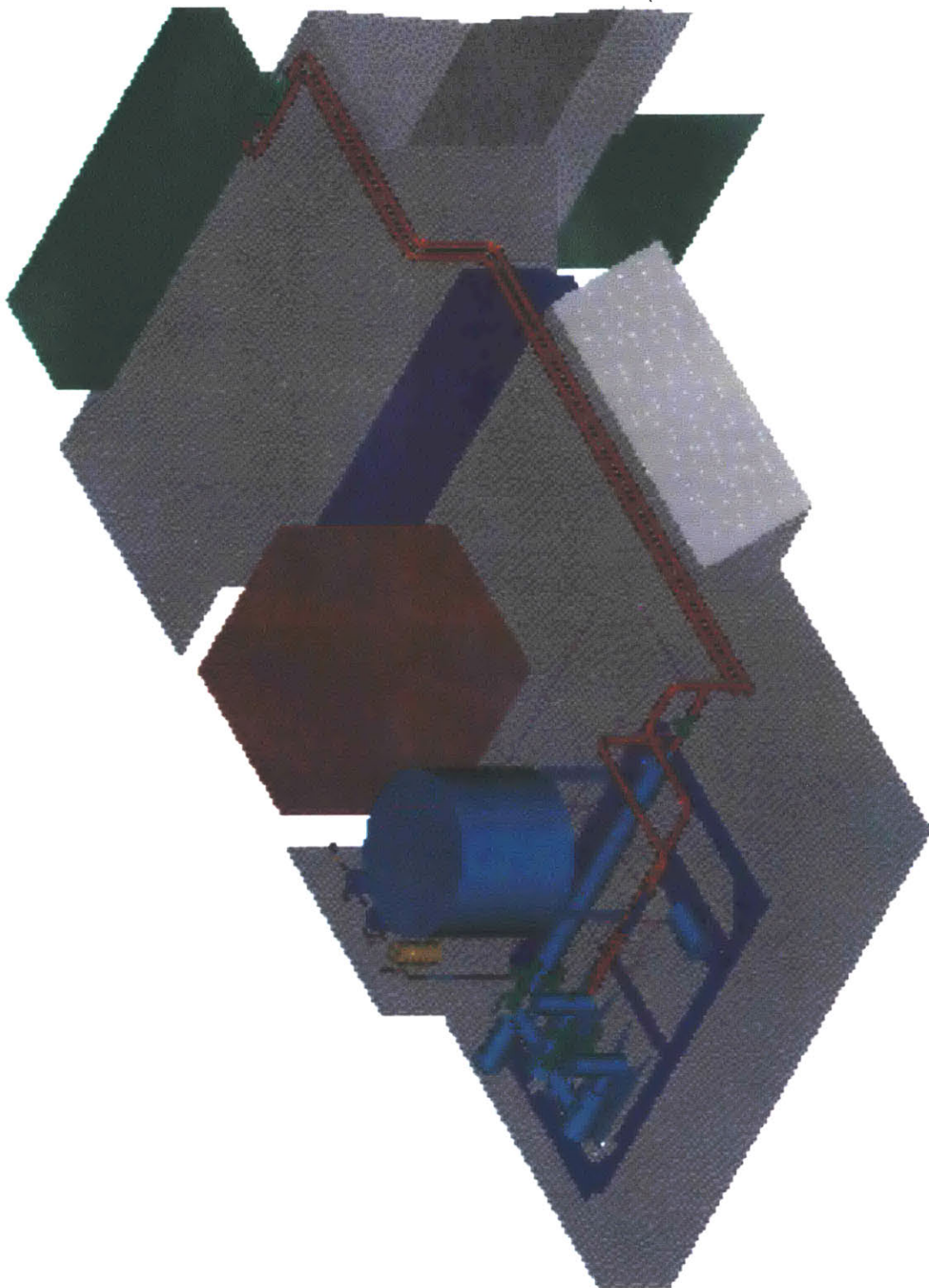


Figure 5-2. Solid diagram of heat removal system on top of the medical room.